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Spatial variability of organic matter in Massachusetts soils /

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SPATIAL VARIABILITY OF ORGANIC MATTER

IN

MASSACHUSETTS SOILS

A Thesis Presented

By

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Without the help and encouragement of my dear wife, Nahideh Ghaemmagham Farahani, and my two children, Nasim and Arash, this effort could not have been made. I give my thanks to them from the bottom of my heart.

ABSTRACT

Assessment of the spatial variability of soil organic matter content requires processing of large numbers of samples. The rapid loss-on-ignition method was compared with conventional wet oxidation and dry combustion methods. The results showed a significant correlation ($0.53 \leq r \leq 0.98$) between the methods in the A, B, and C horizons of selected Massachusetts soils. Regression models predicting the value of soil organic matter content from extractable aluminum, cation exchange capacity and clay content values were developed to facilitate estimation of soil organic matter content from soil characterization data.

Geostatistical techniques were used to evaluate the spatial variability of organic matter content within selected mapping units in short and long transects (50 or 80; and 1200 m respectively) at 0.5, 1, and 15 m sampling intervals. The results showed strong trends with distance. Semivariograms indicated that geostatistical procedures were less applicable and that classical statistical analysis were more suitable to assess organic matter distribution within single mapping units. Statistical analysis using t-test and F tests, revealed no significant variation of soil organic matter content within two Hadley mapping units, but significant variability was detected within Agawam and Limerick mapping units.

Analysis of the spatial dependency of soil organic matter content for a 1200-m transect and a 6.14 ha rectangular grid encompassing different soil series using semivariograms, indicated that organic matter content was spatially variable by soil series. The variability of organic matter in the Limerick series was higher than that of the Hadley soil series. Kriging was used to predict organic matter contents at unsampled locations. Correlation coefficients ($r^2 = 0.873$ for a single transect) and ($r^2 = 0.438$ for a grid) were obtained between measured and predicted values. The results indicated the presence of anisotropy along the long side of the rectangular grid indicating that the sampling interval

distance in that direction could be increased by a factor of 2.75. A block-kriged map, was prepared based on the logarithms of values of percent organic matter content in the aforementioned grid.

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CHAPTER III

ORGANIC MATTER DISTRIBUTION IN MASSACHUSETTS SOILS

Introduction

Procedures used to determine soil organic carbon or matter content may be grouped into wet oxidation (WO), dry combustion (DC) and loss-on-ignition (LOI) methods. In the wet oxidation method (Walkley and Black, 1934; Allison, 1960; Heanes, 1984; Piccolo and Santroni, 1986; Amacher et al., 1986), the soil sample is digested in a mixture of H_3PO_4 and H_2SO_4 in the presence of $K_2Cr_2O_7$. The organic carbon is oxidized by the $Cr_2O_7^{2-}$ and the organic carbon content is determined from the amount of unreduced $Cr_2O_7^{2-}$ by back titration with Fe^{2+}.

The dry combustion method (Tiessen et al., 1981; Nelson and Sommer, 1982; Richardson and Bigler, 1982; Charles and Simmons, 1986; Amacher et al., 1986; Rabenhorst, 1988), involves incineration (~1000°C) of a soil sample in purified oxygen and generation of carbon dioxide. Absorbents in the analytical apparatus measure the amount of evolved CO_2, and based upon that, the percent of soil carbon can be calculated.

The loss-on-ignition method (Davies, 1974; Goldin, 1987) is based on determination of the organic matter content from the loss in mass when the sample is heated at temperatures above 400°C. This method is fairly rapid and simple. By introducing conversion factors, ranging between 0.5-0.58 for the upper horizons, organic carbon content can be estimated.

These different methods of organic carbon or organic matter determination in soil have been the subject of several studies in recent years. Amacher et al. (1986) recorded significant correlation coefficient values (r^2 = 0.956 - 0.981) for the relationship between dichromate-oxidizable organic carbon (DOOC) and total organic carbon in different soils

using wet oxidation and dry combustion methods. Goldin (1987) indicated a linear relationship between the organic matter content estimated by loss-on-ignition (LOI) and the dry combustion method (r^2 = 0.89). Heanes (1984) determined least significant difference (p = 0.05) values for percent recovery of organic carbon in non-calcareous and calcareous soils using dry combustion and wet oxidation procedures. Richardson et al. (1982) reported a good correlation (r = 0.925 - 0.993) when comparing wet oxidation and dry combustion methods.

This study was aimed at establishing the applicability of the loss-on-ignition method in place of the wet oxidation and dry combustion methods in selected Massachusetts soils, and assessing its relationship to selected physical and chemical soil properties.

Materials and Methods

Forty-eight samples representing the major horizons (A, B, and C) of sixteen soil series were used for this study (Table 3.1). To a large extent, the samples had been previously analyzed for soil survey purposes (Veneman, 1985). This included textural analysis, cation exchange capacity, pH, exchangeable bases, base saturation and extractable iron and aluminum.

Total carbon by dry combustion was determined with a Perkin-Elmer 240 Analyzer (Perkin-Elmer Corp., Instrument Division, Norwalk, Conn.) which simultaneously measures C, H, and N (Nelson and Sommer, 1982). Organic carbon based on the wet oxidation method was determined with method 6A1a (Soil Survey Staff, 1972) and the Modified Mebius Procedure (Nelson and Sommer, 1982) using a conversion factor of 0.77. The loss-on-ignition method by Davies (1974) was used to measure organic matter content.

Table 3.1 List of soil series, classification and location of the soil samples used in the organic carbon and organic matter study.

Soil series	Classification	Location
Agawam	Typic Dystrochrept	Amherst
Broadbrook	Typic Fragiochrept	Amherst
Canton	Typic Dystrochrept	Harvard
Haven	Typic Dystrochrept	Hadley
Hinckley	Typic Udorthent	Belchertown
Lyman	Lithic Haplorthod	Windsor
Nantucket	Typic Fragiochrept	Gay Head
Narragansett	Typic Dystrochrept	Amherst
Paxton	Typic Fragiochrept	N. Brookfield
Rainbow	Typic Fragiochrept	Amherst
Ridgebury	Aeric Fragiaquept	Amherst
Scituate	Typic Fragiochrept	Warren
Shelburne	Typic Fragiochrept	Shelburne Falls
Sudbury	Aquic Dystrochrept	Ipswich
Sutton	Typic Dystrochrept	Hamilton
Windsor	Typic Udipsamment	E. Sandwich

Results and Discussion

Soil organic carbon content varies with depth (Figures 3.1,2,3 and 4). No appreciable differences were observed in values with either WO and DC methods. Organic matter content determined with the LOI method always was higher than values for the WO and DC methods. This difference was fairly constant by a factor of 1.97.

Results of the two different procedures for wet oxidation, Mebius and Walkley-Black, were highly correlated (r = 0.986) and these methods can be used interchangeably.

Analysis of variance using the SAS (1985) program indicated a highly significant correlation (Fig. 3.5) between the LOI method and the WO or DC methods in the A and B horizons in all of the profiles (Table 3.2). The results suggest that the LOI method can be used in place of the WO or DC method in acid noncalcareous soils. Regression analyses were performed to relate the different methods of organic carbon determination with selected physical and chemical properties routinely determined for soil survey purposes. A significant correlation was found among the different methods and CEC; extractable Al by pyrophosphate (ALPY) and dithionate (ALDI); extractable iron by pyrophosphate (FEPY) and dithionate (FEDI); and clay, silt and sand contents in the different horizons (Table 3.3). Based on these regression equations, it is possible to predict organic carbon using CEC, Al, Fe, or clay content in either A, B, or C horizon. The suggested models can be applied in noncalcareous soils with pH levels ranging from 4 - 6.5.

The results show that in the A-horizon, when using the DC method, 98% of the variation in the organic carbon content may be accounted for by the extractable aluminum. The results indicate that in the WO and LOI methods, 11% and 91%, respectively, of the variation of organic carbon could be accounted for extractable aluminum.

In the B-horizon, 94%-96% of the variation of organic carbon is related to the cation exchange capacity. With the DC and WO methods in the C horizon, 80% - 94% of variation

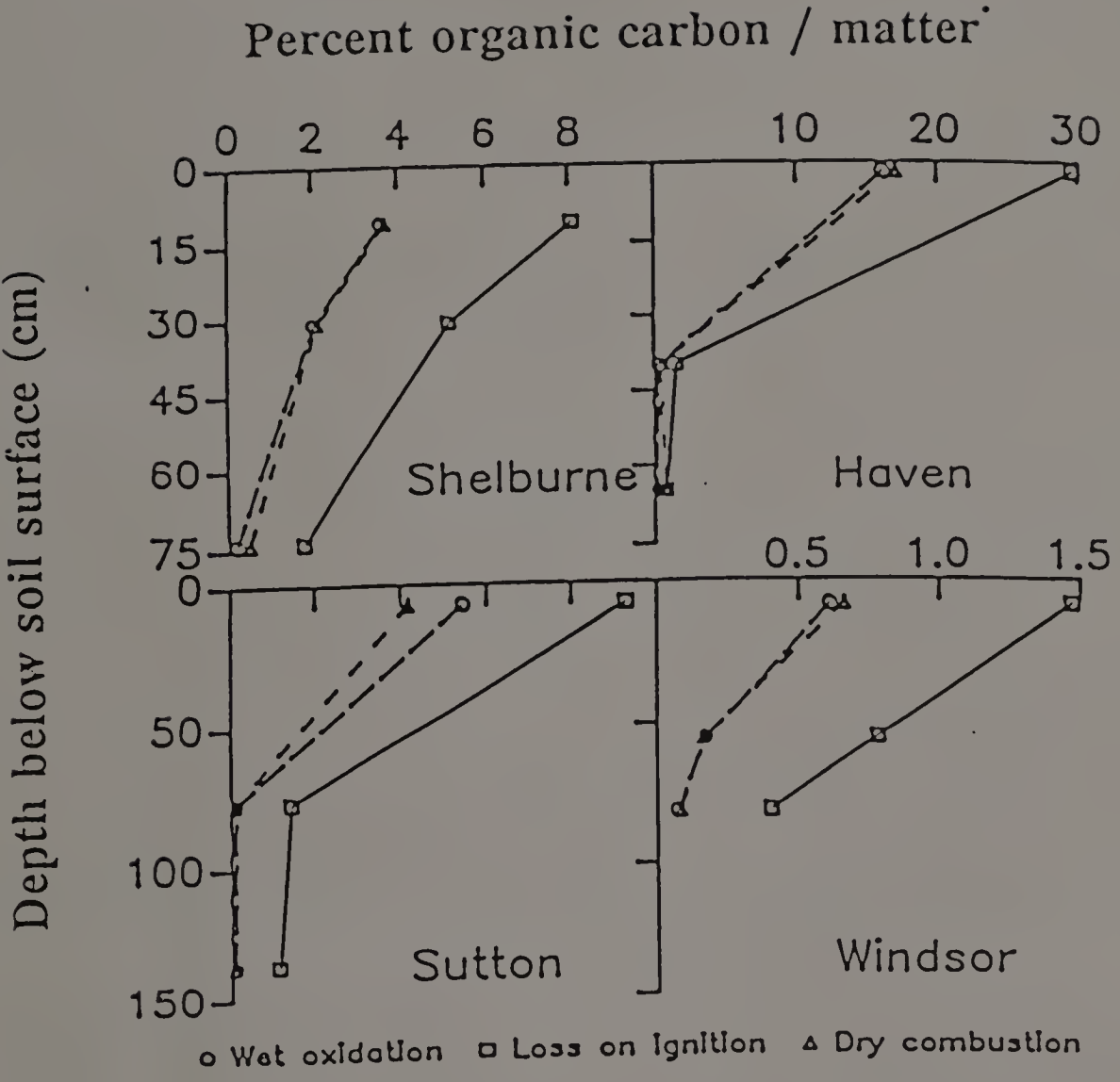


Fig. 3.1 Organic carbon/matter* content in Shelburne, Haven, Sutton and Windsor soils using wet oxidation, loss-on-ignition, and dry combustion methods.
* For loss-on-ignition method, data presented as percent organic matter.

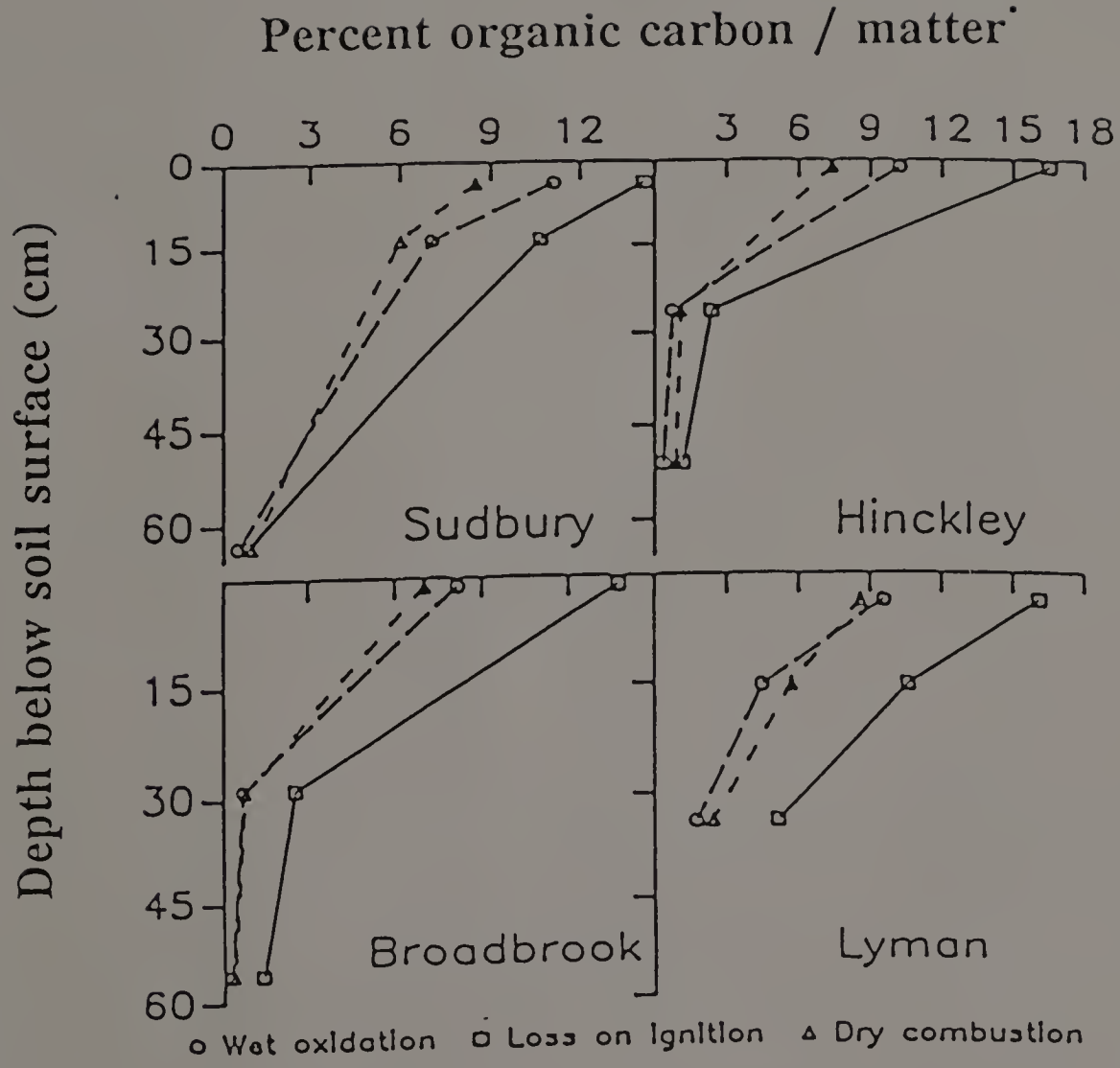


Fig. 3.2 Organic carbon/matter* content in Sudbury, Hinckley, Broadbrook and Lyman soils using wet oxidation, loss-on-ignition, and dry combustion methods.
* For loss-on-ignition method, data presented as percent organic matter.

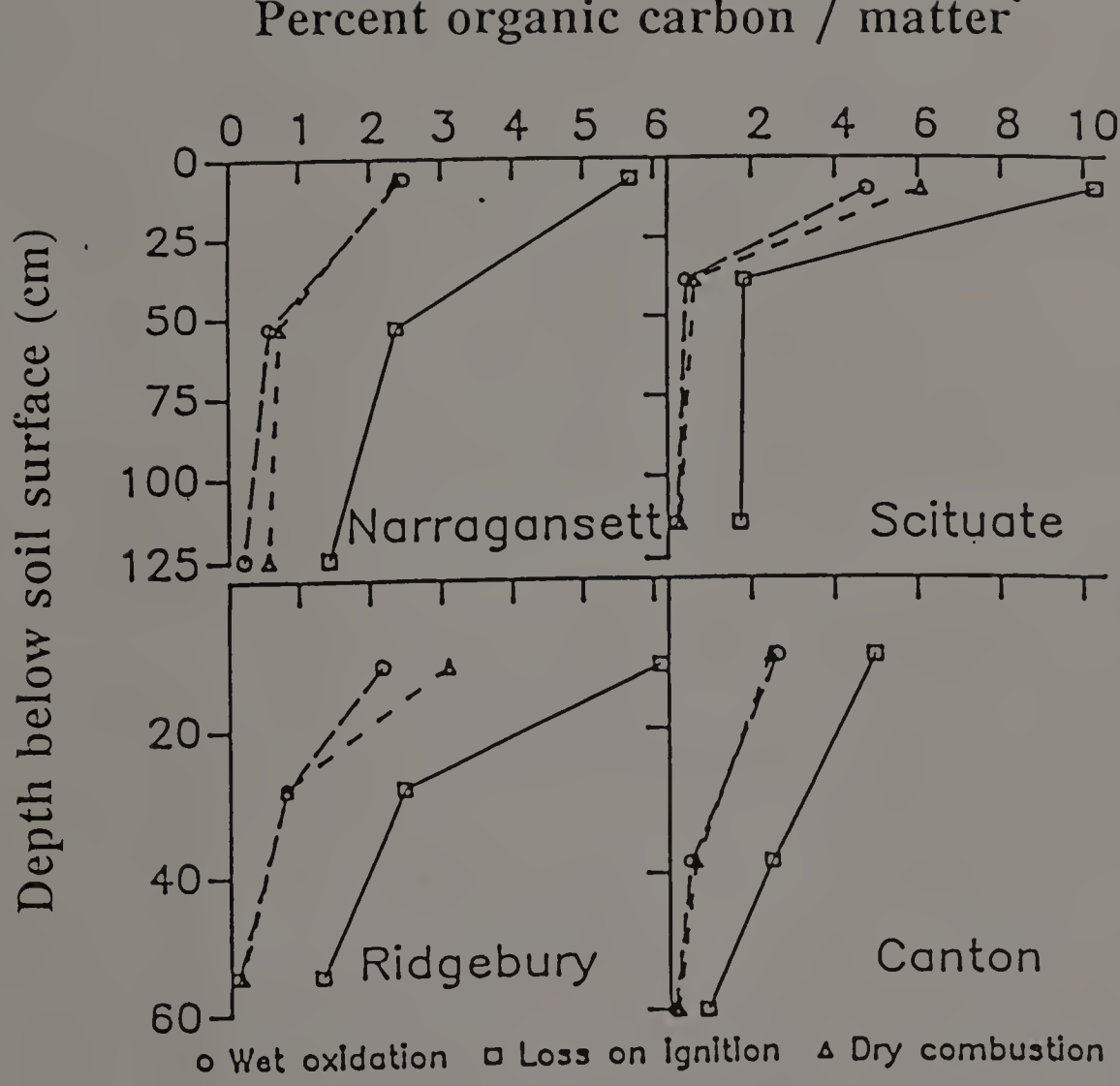


Fig. 3.3 Organic carbon/matter* content in Narragansett, Scituate, Ridgebury, and Canton soils using wet oxidation, loss-on-ignition, and dry combustion methods.
* For loss-on-ignition method, data presented as percent organic matter.

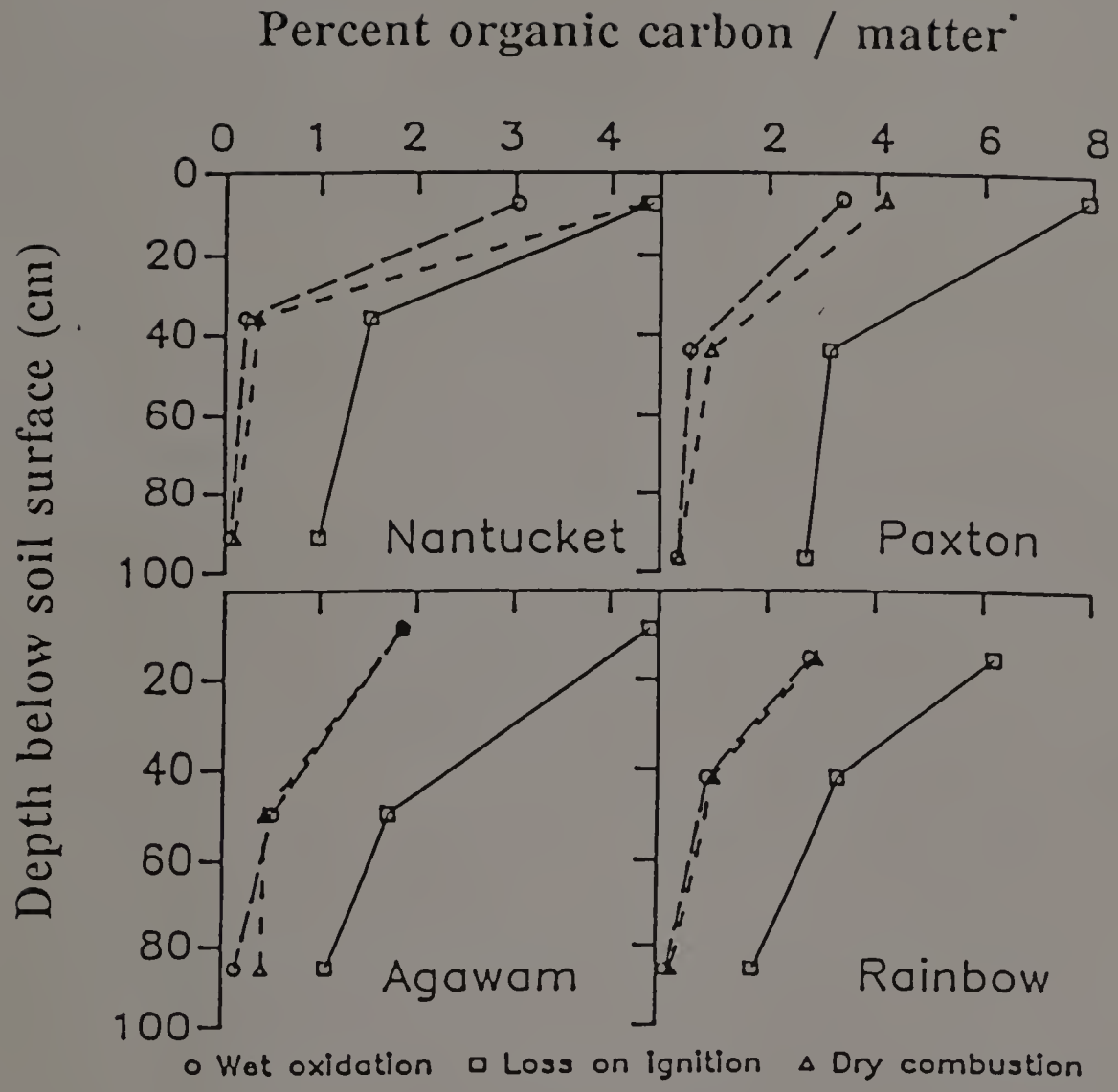


Fig. 3.4 Organic carbon/matter* content in Nantucket, Paxton, Agawam, and Rainbow soils using wet oxidation, loss-on-ignition, and dry combustion methods.
* For loss-on-ignition method, data presented as percent organic matter.

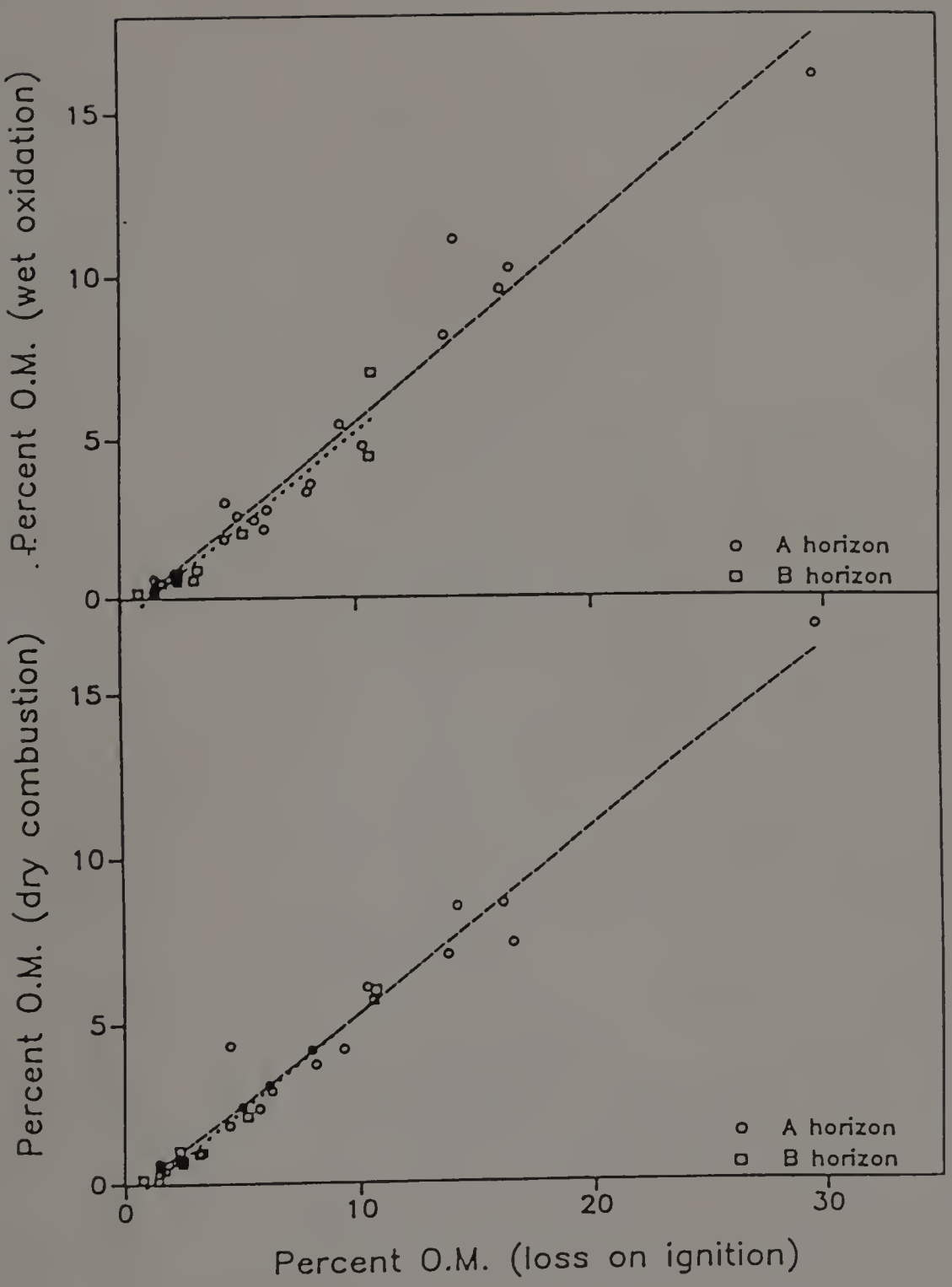


Fig. 3.5 Relationship between loss-on-ignition method with wet oxidation and dry combustion methods in A and B horizons.

Table 3.2 Prediction of organic carbon content values for the dry combustion (DC) and wet oxidation (WO) methods using loss-on-ignition (LOI) method as the independent variable in different soil horizons.

Dependent Variable	Independent Variable	Horizon	Slope	Intercept	r^2
DC	LOI	A	0.6	-0.03	0.95
		B	0.6	-0.63	0.98
		C	0.4	-0.08	0.53
WO	LOI	A	0.52	-0.26	0.70
		B	0.60	-0.76	0.91
		C	0.32	-0.19	0.74

Table 3.3 Regression equations for predicting organic matter content based on selected chemical properties.

Method	Horizon	Regression equations
DC	A	DC = 8.64 ALPY - 0.36 FEDI + 1.97
WO	A	WO = 2.77 ALPY + 0.1 CEC + 0.4
LOI	A	LOI = 8.82 ALDI - 2.25 CEC + 16.08
DC	B	DC = 0.13 CEC + 0.57 FEPY - 0.03 CLAY - 0.14
WO	B	WO = 0.57 ALDI + 0.13 CEC - 0.58
LOI	B	LOI = 1.53 ALDI + 0.29 CEC - 0.37
DC	C	DC = 2.93 ALPY + 0.008 SAND - 0.3
WO	C	WO = 2.14 ALPY + 0.1
LOI	C	LOI = 0.26 CEC - 0.007 SILT + 0.13

is related to extractable Al. In the LOI method in the C horizon 98% of the variation of is related to CEC.

The current study provide evidence that organic matter content in selected Massachusetts soils is significantly related to extractable Al and CEC. Sahrawat (1983) showed that 60% of the variation in CEC was related to organic matter content, while Drake and Motto (1982) reported that organic matter and clay content accounted for 59% of the variation in CEC. Low partial r^2 values indicated that organic matter content usually was not strongly related to clay content in the soils studied.

The good correlation between organic matter content and extractable Al can be explained in part by the interaction of Al with humic and fulvic acids (Schnitzer and Kodama, 1977; Kodama and Schnitzer, 1980) leading to the formation of insoluble hydroxy-aluminum-organic complexes. The occurrence of these complexes depends upon the ratio and nature of the organic acids to Al and pH. Low-molecular-weight organic acids are of paramount importance in the translocation of Al and Fe (Huang and Violante, 1986). These authors postulated that the more strongly organic ligands complex Al, the greater their influence on the precipitation of Al. By increasing the amount of organic matter in the soil solution, the greater the blocking of Al sites.

Conclusions

The rapid loss-on-ignition method was compared to the conventional wet oxidation and dry combustion methods. The results revealed that loss-on-ignition method consistently yielded greater values than the wet oxidation and dry combustion methods. Furthermore, the loss-on-ignition method was highly correlated to the wet oxidation and dry combustion methods. The results indicated that the loss-on-ignition method could be used to estimate soil organic carbon content. Regression analysis showed that without directly measuring organic carbon content, these values can be estimated by using Al, CEC, or clay content.

CHAPTER IV

SPATIAL VARIABILITY OF ORGANIC MATTER

Introduction

Reliable estimates of the variability of soil organic matter require knowledge of its distribution pattern. Estimating the degree of variability and assessing the source of the variance for various soil properties has been the subject of several studies (Warrick and Nielsen, 1980; Hajrasuliha et al., 1980; Vieira et al., 1981; Gajem et al., 1981; Yost et al., 1982; Dahiya et al., 1984; Saddig et al., 1985; Webster, 1985; Riha et al., 1986; Trangmar et al., 1986; Trangmar et al., 1987; Schimel et al., 1988; West et al., 1989). Most of these efforts considered some physical, chemical and geomorphological aspects of the landscape. In general, parent material, climate, topography, various physical and chemical processes, and biological activity are known sources of variability in the natural landscape.

Considerable effort has been extended to estimate the variability of soils using a limited number of observations under the assumption that measured properties represent the variability of unsampled locations in the landscape. For example, soil survey characterization studies typically are conducted by collecting point samples assuming that they represent neighboring points, and that the observations are random and spatially independent regardless of their location in the field. With this approach, mean, variance, standard deviation and coefficient of variation for various soil properties can be estimated. This method, however, does not necessarily provide a picture of the true variation of the soil properties, because the calculated variance does not consider the distance between observations (Saddig et al., 1985). In addition, often a normal distribution is assumed which may not be truly representative.

In recent years, a new approach to spatial analysis has been developed commonly referred to as the geostatistical method (Matheron, 1963). This technique, also known as the regionalized variable theory, considers differences between soil properties at different locations (Webster, 1985). Geostatistical methods provide a means to understand the spatial dependency of soil variability which can not be obtained from standard frequency distribution analysis.

The degree of heterogeneity of soil in a landscape determines the spatial dependency of any property. In general, the degree of dependency for any soil property varies within a wide spectrum of which, randomness represents one end and the presence of strong trends the other end (Fig. 4.1). Within these two extremes, the values of parameters may not be independent of each other and application of spatial analysis then is the appropriate framework for expressing these relationships.

Knowledge of the variability in soil organic matter content is essential in predicting the soil chemical behavior in regard to the behavior of fertilizers, pesticides and other organic chemicals. In this chapter the spatial variability of soil organic matter is assessed in selected soil mapping units representing different parent materials.

Materials and Methods

Site Selection and Sampling

Soil mapping units, representative of the following series were sampled in duplicate:

Agawam series (Typic Dystrochrepts, coarse loamy over sandy, mixed, mesic), developed in well-drained glaciated outwash.

Charlton series (Typic Dystrochrepts, coarse loamy, mixed, mesic), formed in well-drained glacial till on uplands.

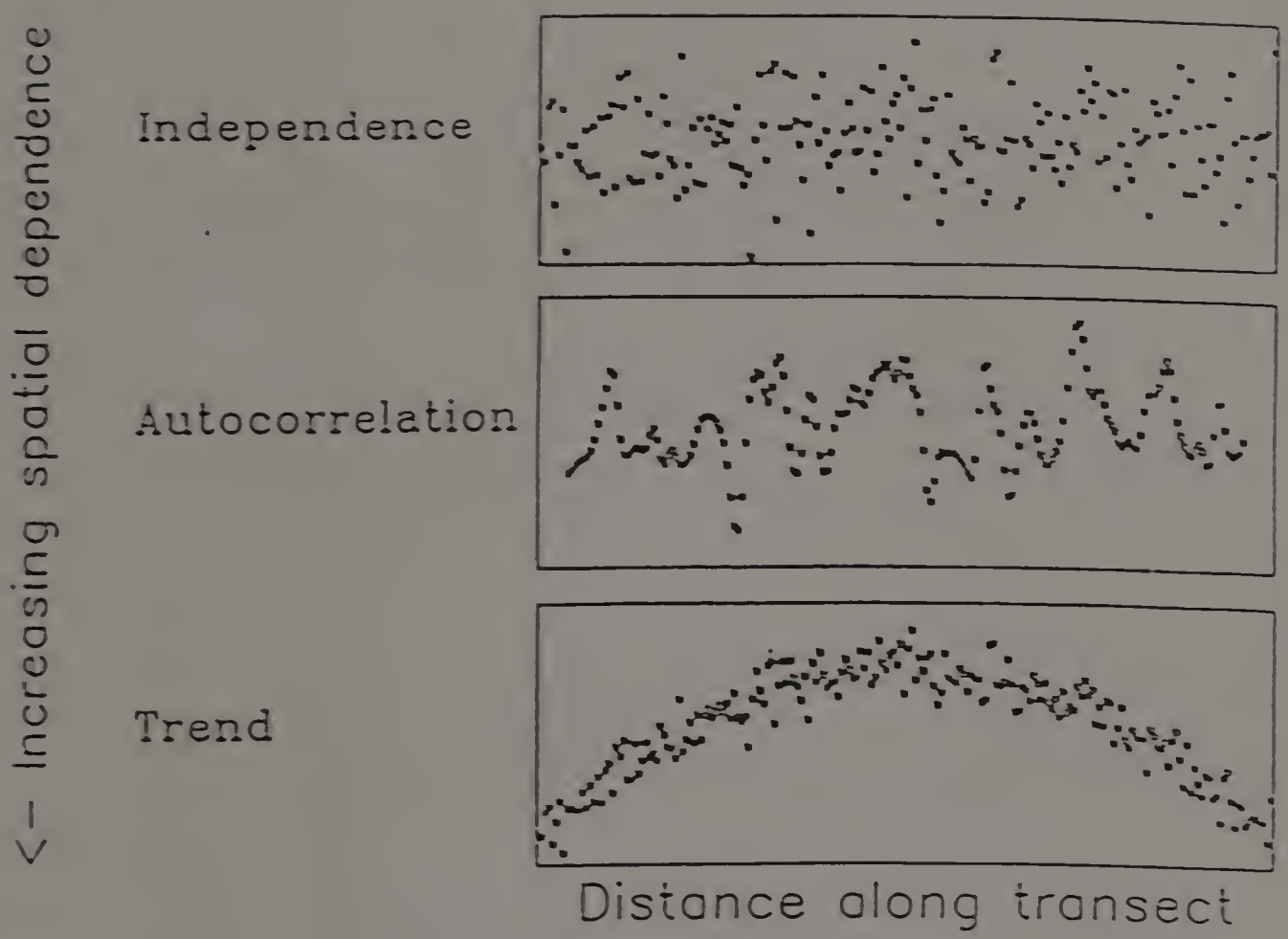


Fig. 4.1 Diagrammatic representation of the possible degrees of spatial dependency of organic matter content along transects in soil.

Hadley series (Typic Udifluvents, coarse silty, mixed, nonacid, mesic), developed in well-drained alluvial deposits.

Limerick series (Typic Fluvaqents, coarse silty, mixed, nonacid, mesic), formed in poorly or somewhat poorly drained alluvial deposits.

All mapping units have been under cultivation (mostly sweet corn) for decades. The annual temperature is 47°F. Mean annual precipitation is 46 inches (Swensen, 1981). Precipitation is evenly divided throughout the year, approximately 40% of precipitation occurs during the growing season. To establish a proper sampling distance protocol, the Charlton and Hadley series were sampled every 0.5 and 1 m along two 50-m and 80-m transects oriented approximately perpendicularly to each other in north-south and east-west directions. In each sampling site, cores (2.5 cm in diameter) were obtained from the upper A-horizon (0-15 cm). Soil organic matter content was evaluated using the loss-on-ignition method (Davies, 1974).

Results and Discussion

Variation of Soil Organic Matter Content in Short Transects

Organic matter plotted as a function of distance along the transects is presented in Fig. 4.2, 3, and 4. The data indicated that the organic matter distribution along short transects (50 and 80 m) within single mapping units at 0.5 and 1 m sampling intervals, did not satisfy the requirement of autocorrelation. Semivariance analysis indicated a periodic variation within transects. The periodicity in the semivariogram for the Hadley soil (Fig. 4.5) showed that measured values for organic matter content taken about 6, 24, and 35 m apart showed more dissimilarity than that of measurements taken about 12, 18, and 40 m apart. Samples taken about 40 m apart tended to show greater similarity.

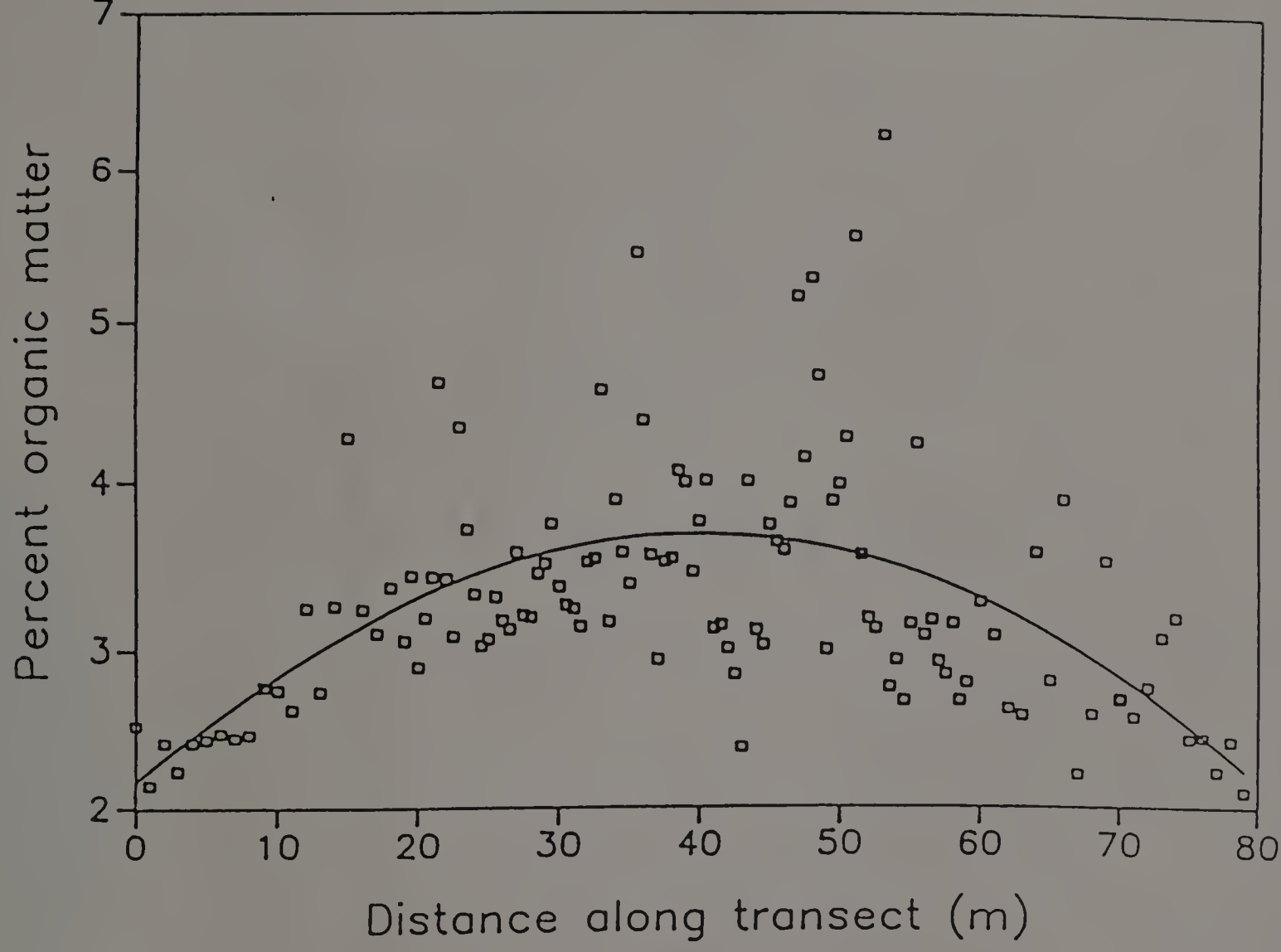


Fig. 4.2 Evidence of a strong trend in the distribution of organic matter content along a transect within a Hadley mapping unit at 1 m sampling intervals.

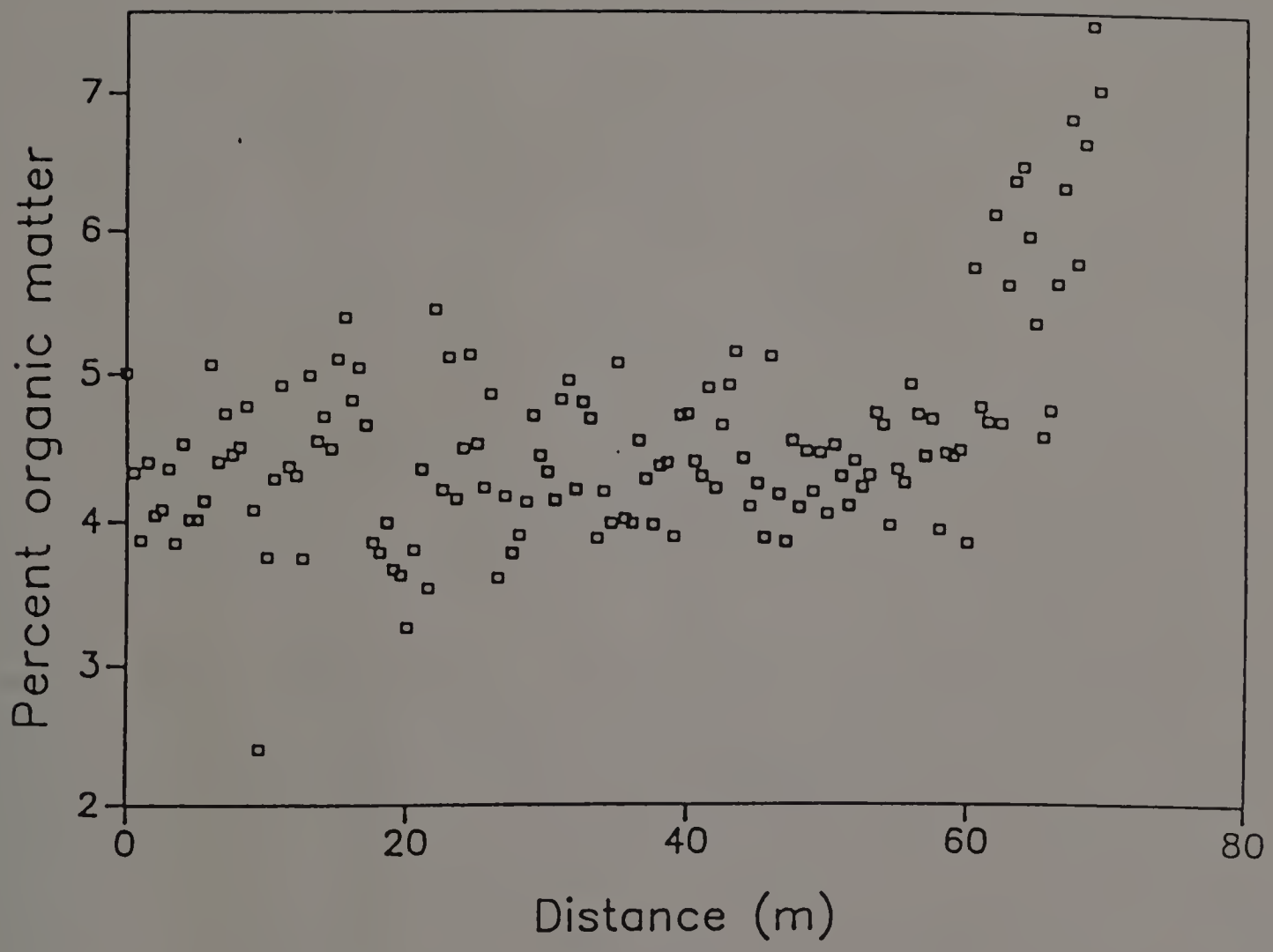


Fig. 4.3 Distribution of organic matter along another transect within a Hadley mapping unit at 1 m sampling intervals.

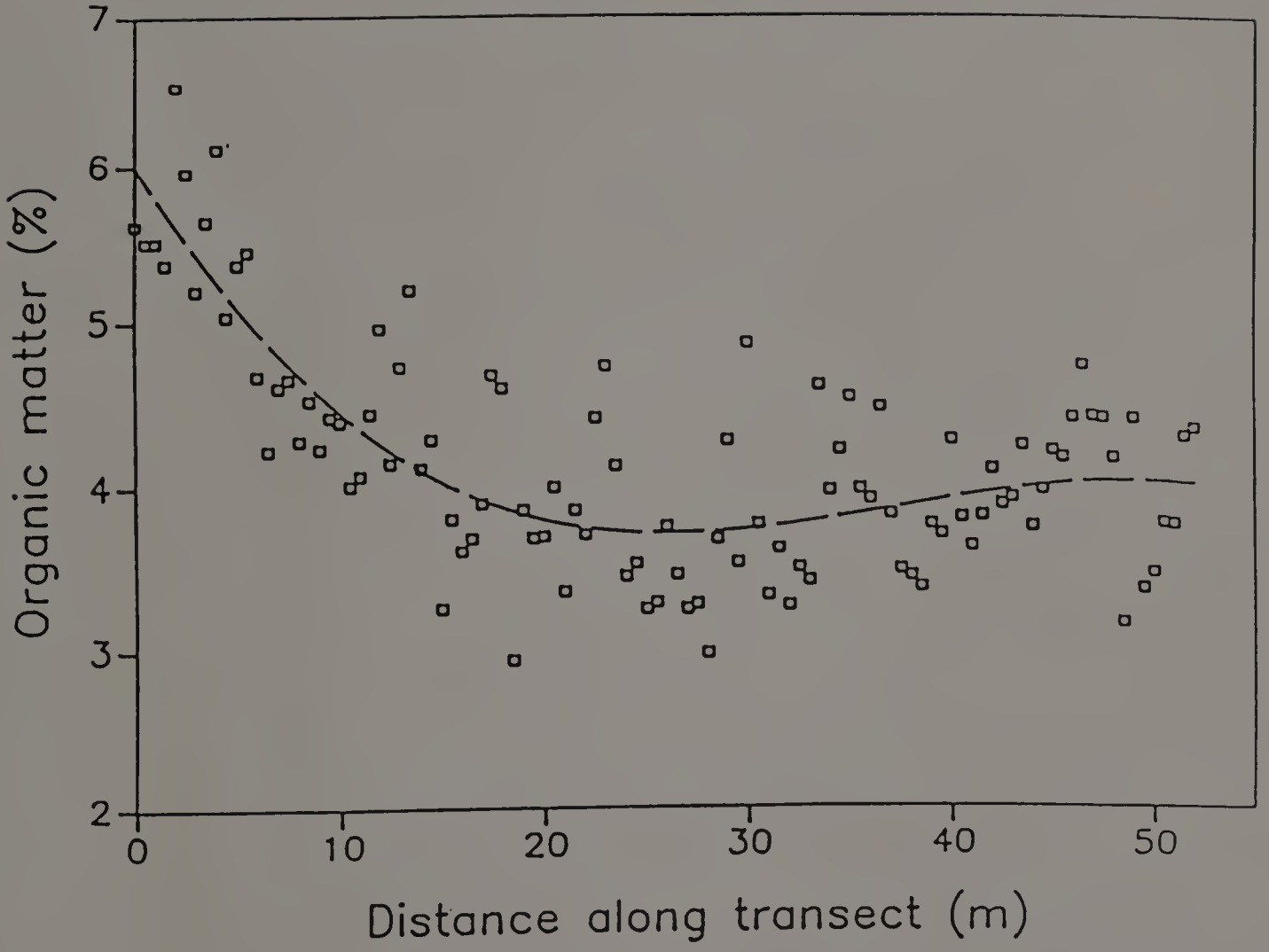


Fig. 4.4 Evidence of strong trend in the distribution of organic matter along a transect in a Charlton mapping unit at 0.5 m sampling intervals.

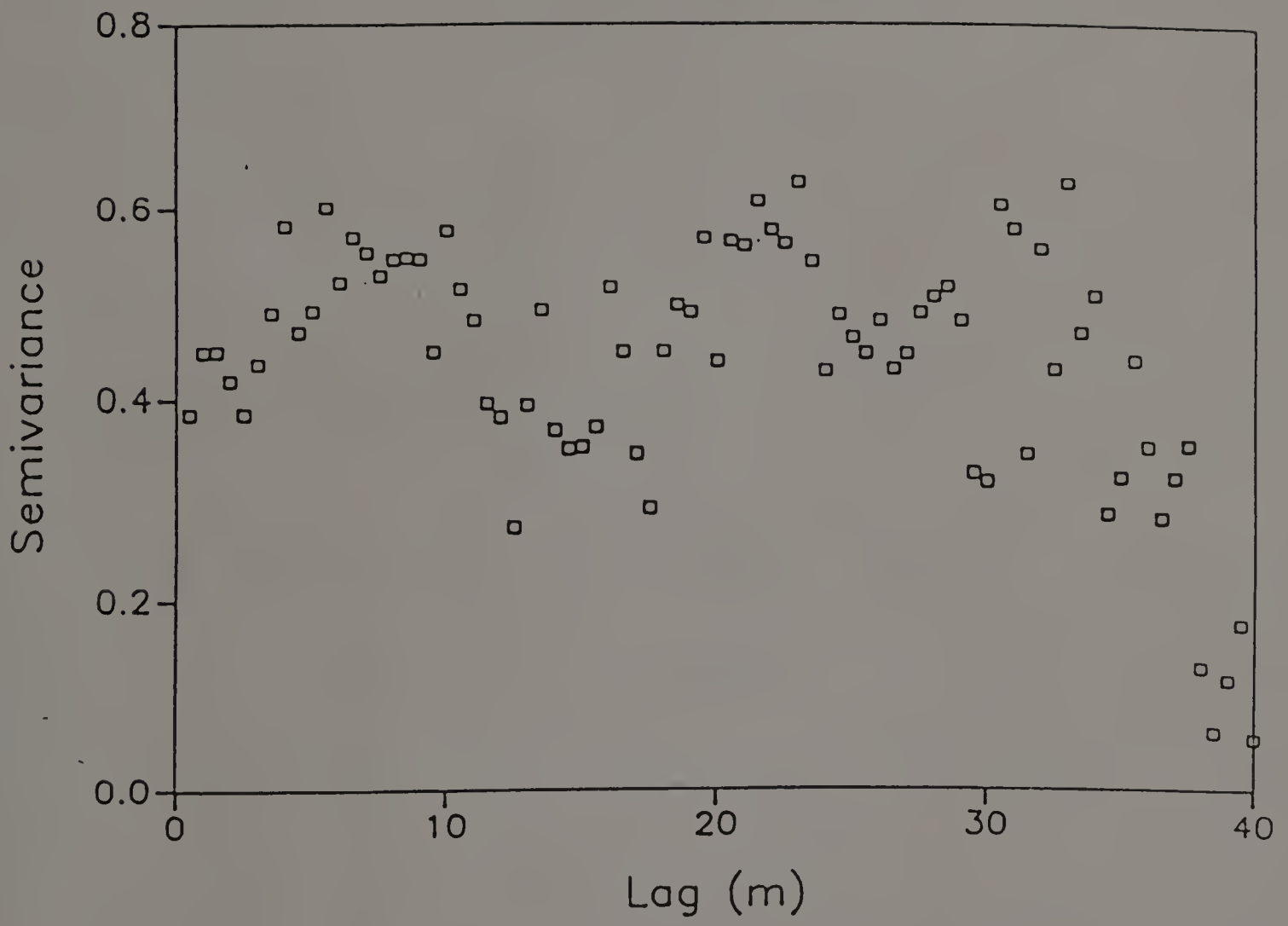


Fig. 4.5 Semivariogram of residual organic matter content along a transect in a Hadley mapping unit based on 1 m sampling intervals.

In one of the Charlton transects (Fig. 4.6), the semivariogram indicated that locations about 1, 32, 43, and 49 m apart, were more similar than those which were with about 15, and 45 m apart. In a second transect of the Charlton mapping unit (Fig. 4.7), measured values 10, 20, 28, 40, and 47 m apart, again tended to be much more similar than values 5, 15, and 35 m apart.

In all of the three aforementioned semivariograms, the ratio of sill values to nugget values (more information about geostatistical procedures is provided in appendix B), was low. These ratios were about 0.5 / 0.4 for the Hadley soil (Fig. 4.5), 0.2 / 0.1 for the Charlton soil (Fig. 4.6), and 0.21 / 0.15 for the Charlton soil (Fig. 4.7). These low values indicated similarity among the measured values.

The general structure of the semivariograms indicated that within single mapping units, the distribution of organic matter exhibited a strong spatial dependency. In that case, the classic statistical analysis procedures are more appropriate for variability analysis.

Determination of Sampling Intervals

Suitable sampling intervals for the longer transects were determined to be 15 m. This was based on the observations of existing trends in the short transects. By selectively removing samples from the data base, i.e. selectively varying the distance between sampling points, autocorrelation was observed. Considering the requirement of at least 80 samples for running the geostatistical analysis, the minimum length of a long transect was estimated to be at least 1200 m.

Variation of Organic Matter Content in Long Transects

To evaluate the soil organic matter content variability, one mapping unit of the Hadley series was sampled in two 1200-m long transects perpendicular to each other at 15

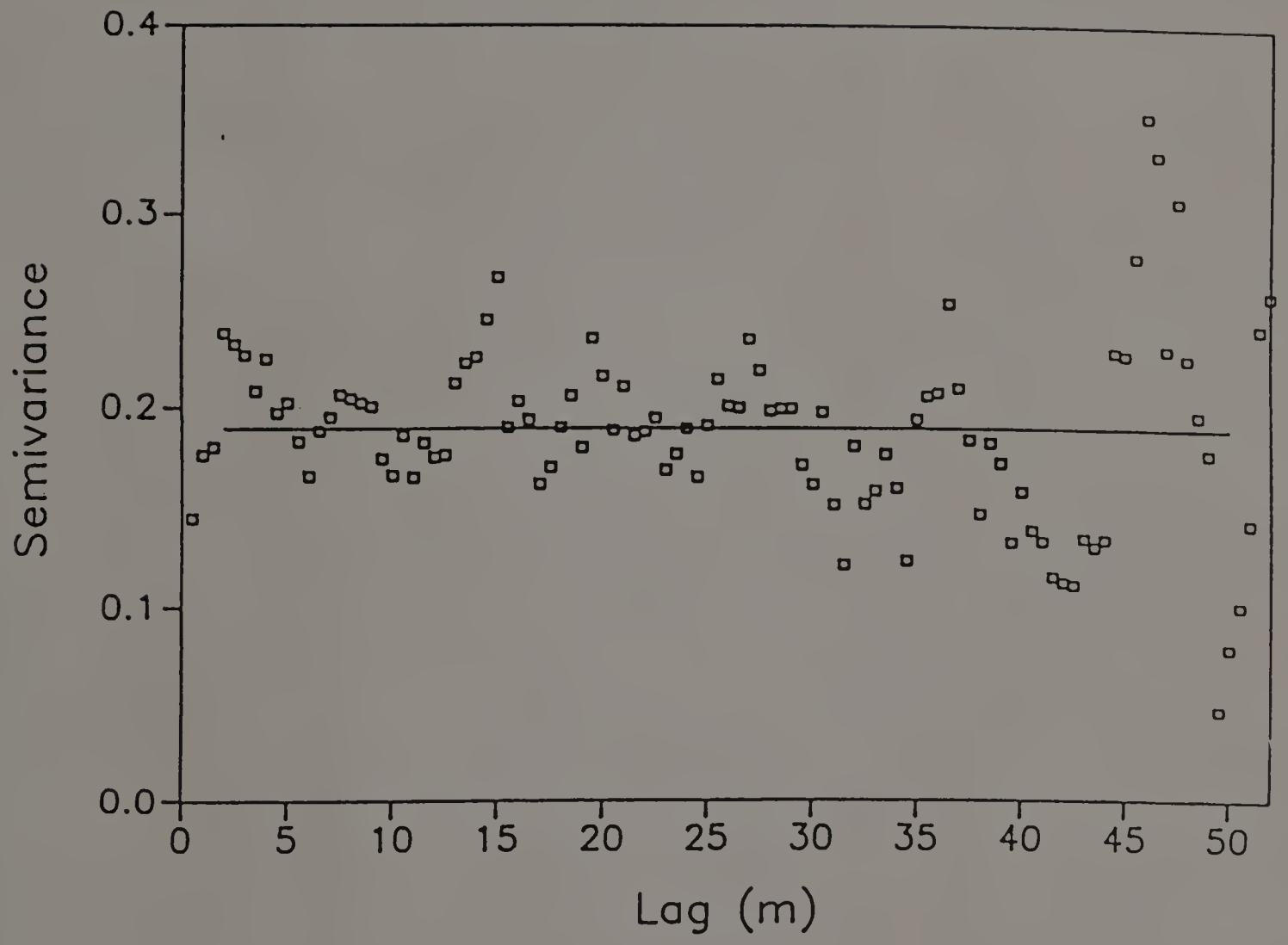


Fig. 4.6 Semivariogram of residual organic matter content along a transect in a Charlton mapping unit based on 0.5 m sampling intervals.

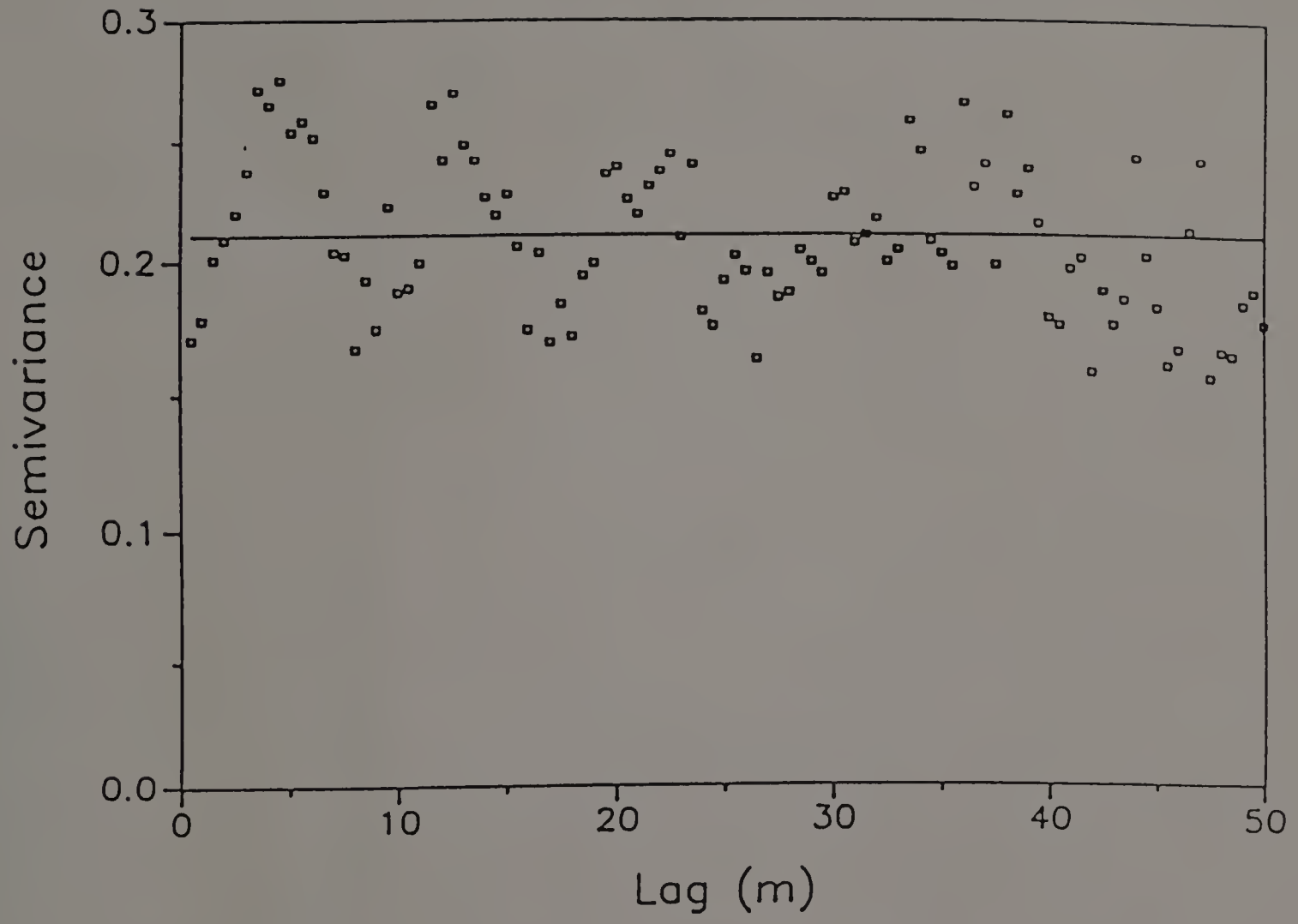


Fig. 4.7 Semivariogram of residual organic matter content along another transect in a Charlton mapping unit based on 0.5 m sampling intervals.

m sampling intervals. The results still exhibited a significant trend along both transects (Fig. 4.8, 9).

The distribution of the organic matter content in the transects at 15 m sampling intervals, showed little autocorrelation. The semivariogram (Fig. 4.10) for the east-west direction still revealed periodicity. The nugget value was almost half of the maximum of the semivariance. The ratio of sill over nugget value was about 0.14 / 0.08. Even though the calculated semivariogram for the north-south direction (Fig. 4.11) showed less of a nugget effect in comparison to the east-west direction, the low ratio value of sill over nugget effect, 0.06 / 0.02, was not large enough to justify applying geostatistical methods to estimate organic matter distribution, regardless of the sampling intervals. It was concluded to be more appropriate in these single mapping units to use classical statistical methods to evaluate variability of the soil organic matter content.

Within and Between Variation of Organic Matter Content

To assess the variability within Hadley, Limerick, and Agawam soil mapping units, duplicate delineations of each were sampled in grids at 15 m intervals. The location of the grids within the mapping unit were selected at random and total number of samples within each grid ranged from 60 to 100. The soil organic matter content was determined using the loss-on-ignition method (Davies, 1974). Contour plots of organic matter content within each mapping unit show the pattern of organic matter distribution (Fig. 4.12, 13, 14). The variability of soil organic matter within and between the mapping units were measured using classical statistics. Analysis of variance, the coefficient of variation CV, and the t-test were employed to evaluate the data. Results showed that there was no significant difference between the two Hadley units, whereas, the Agawam and Limerick delineations were significantly different in organic matter distribution (Table 4.1).

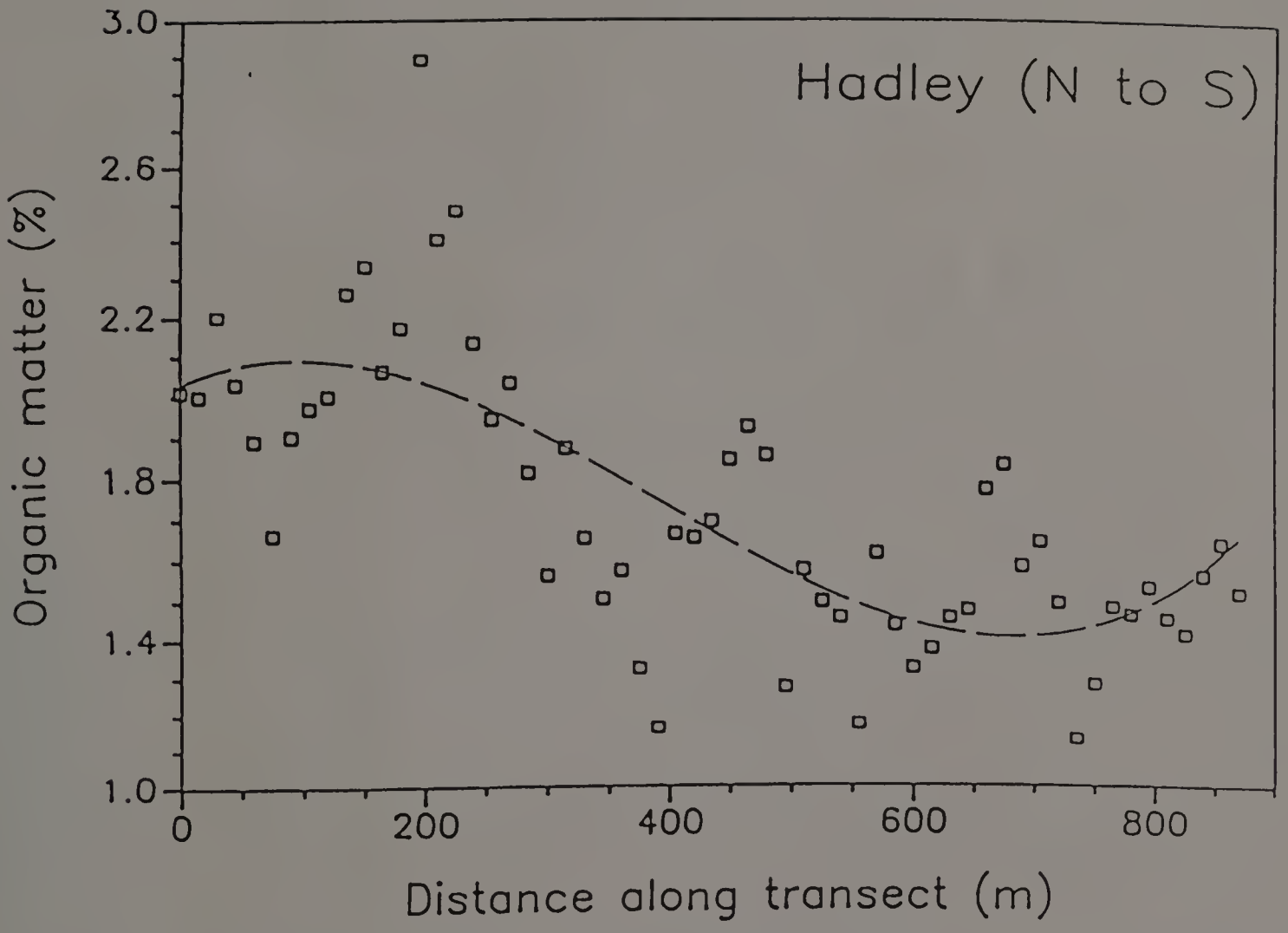


Fig. 4.8 Evidence of trend in the distribution of organic matter content along a north-south transect in a Hadley mapping unit at 15 m sampling intervals.

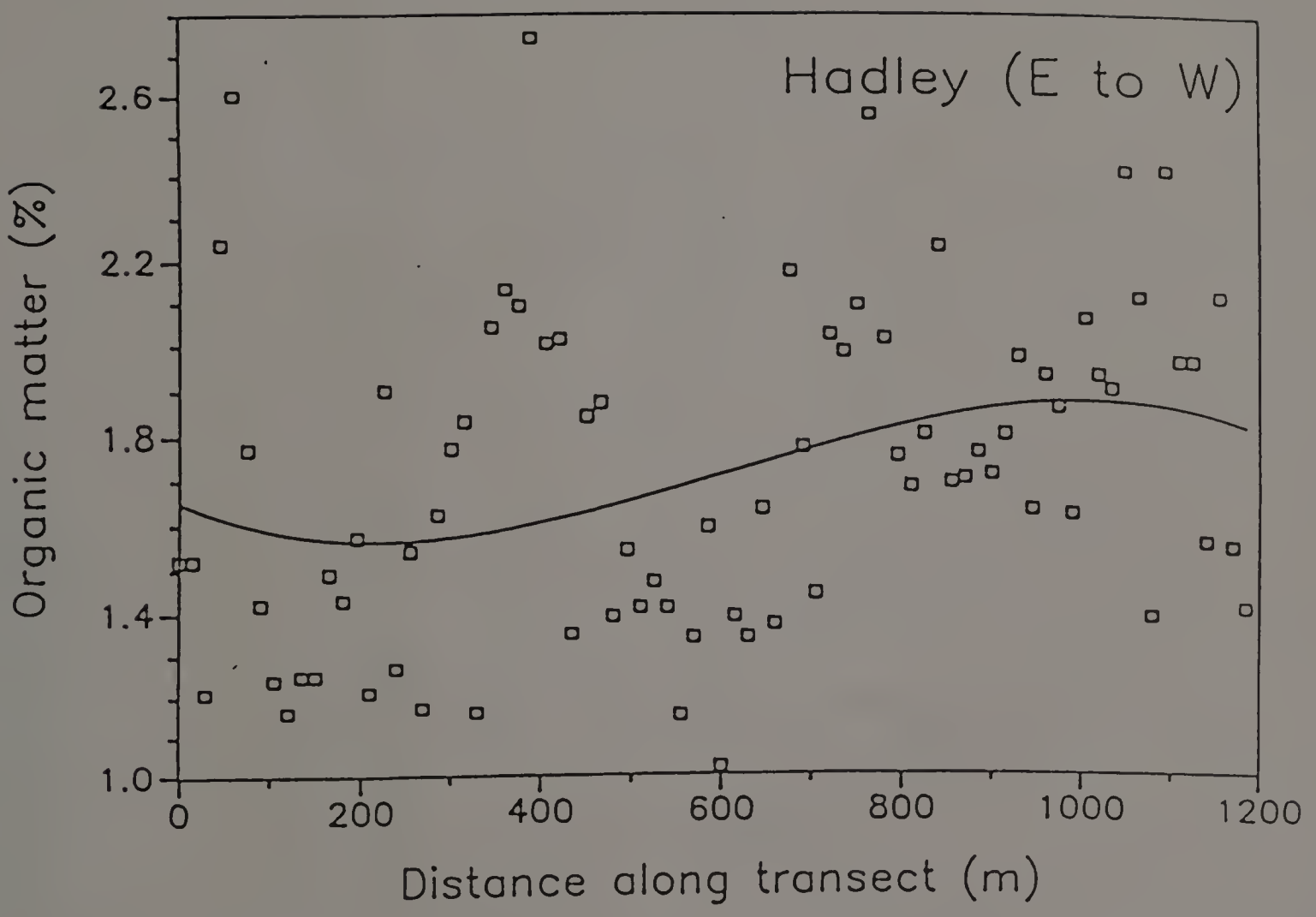


Fig. 4.9 Evidence of trend in the distribution of organic matter content along an east-west transect in a Hadley mapping unit at 15 m sampling intervals.

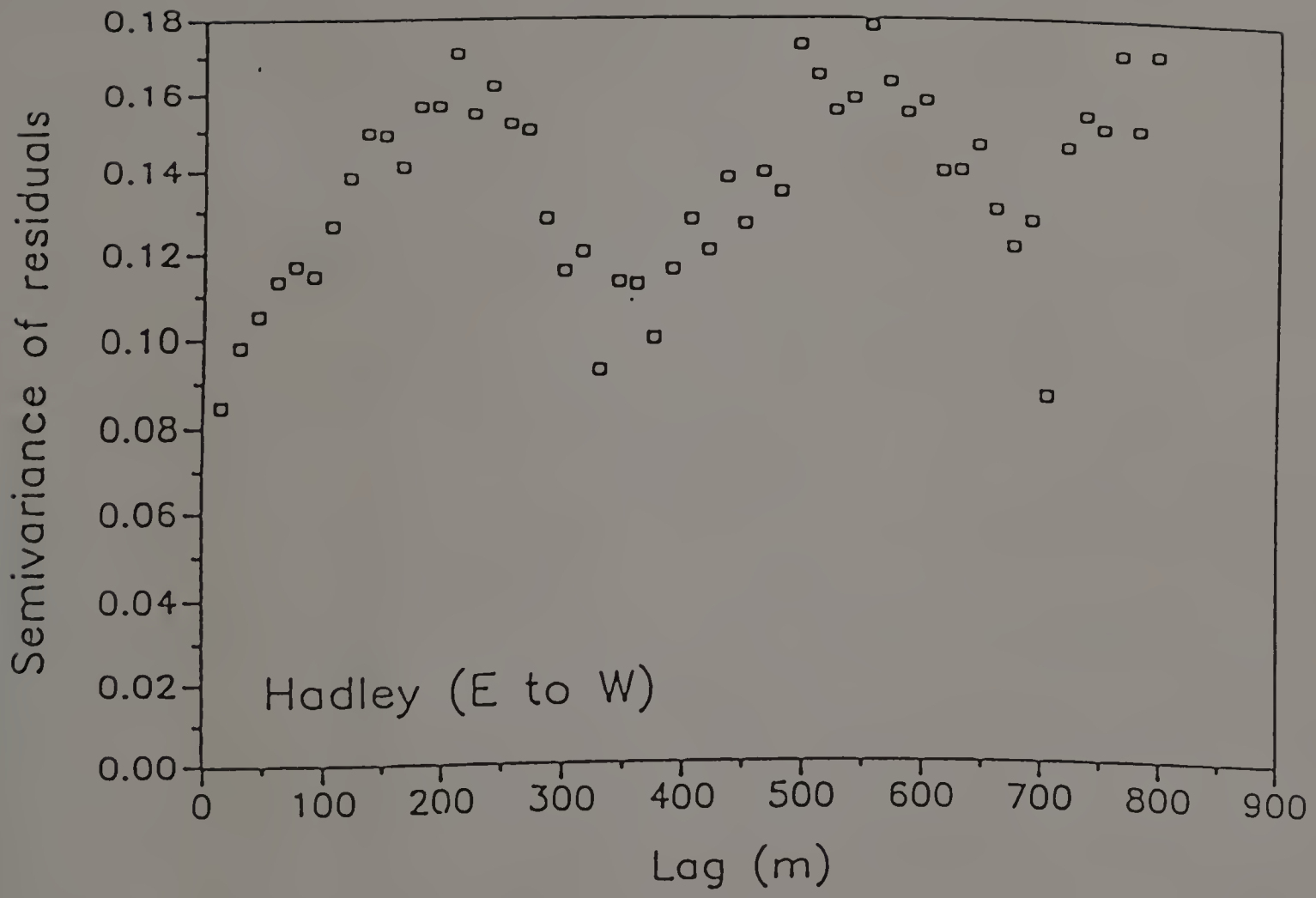


Fig. 4.10 Semivariogram of the regression residuals of organic matter content along an east-west transect in a Hadley mapping unit based on 15 m sampling intervals.

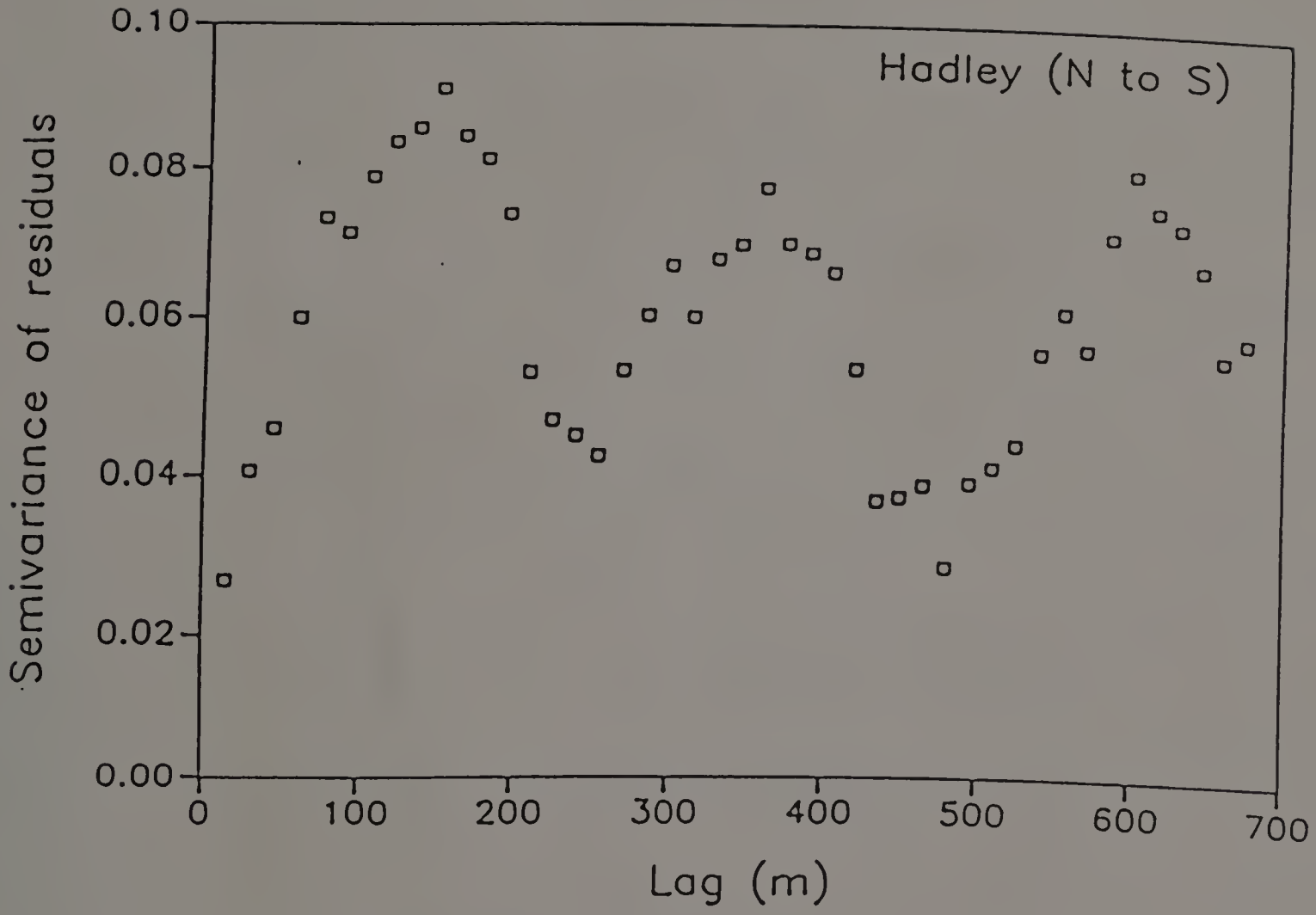
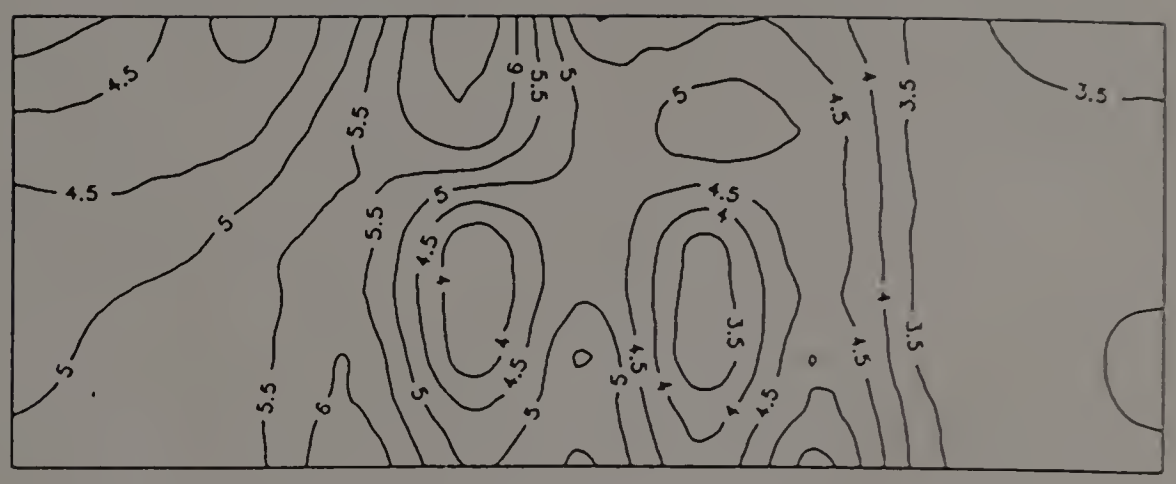


Fig. 4.11 Semivariogram of the regression residuals of organic matter content along a north-south transect in a Hadley mapping unit based on 15 m sampling intervals.



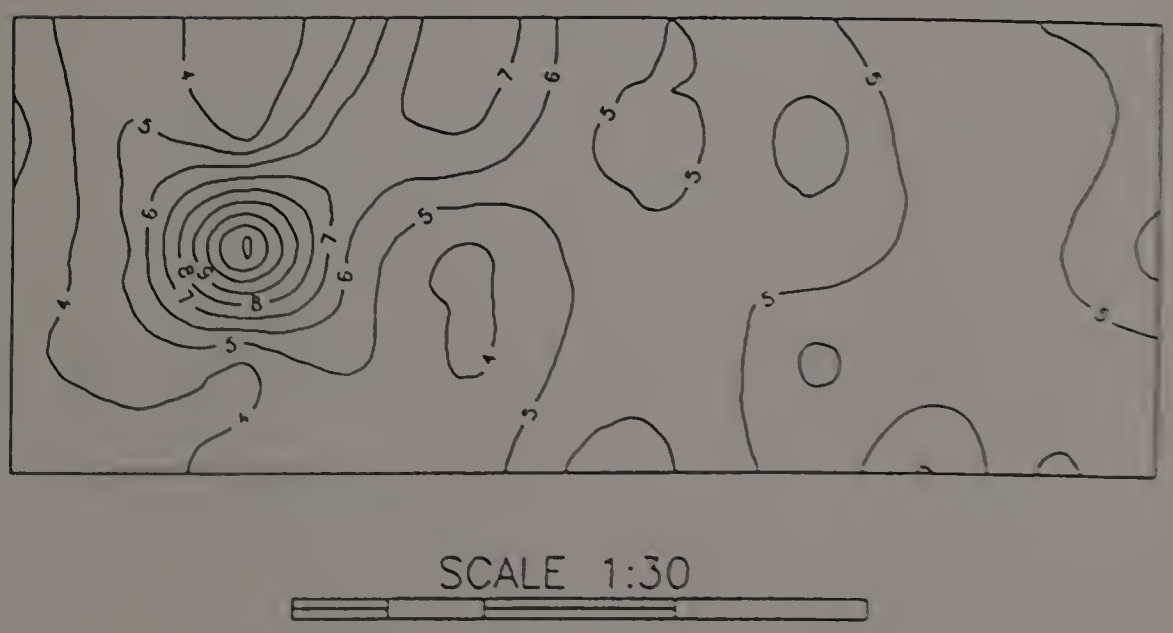


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Fig. 4.12 Distribution of organic matter content (in percent) in a Hadley silt loam mapping unit at two different locations.

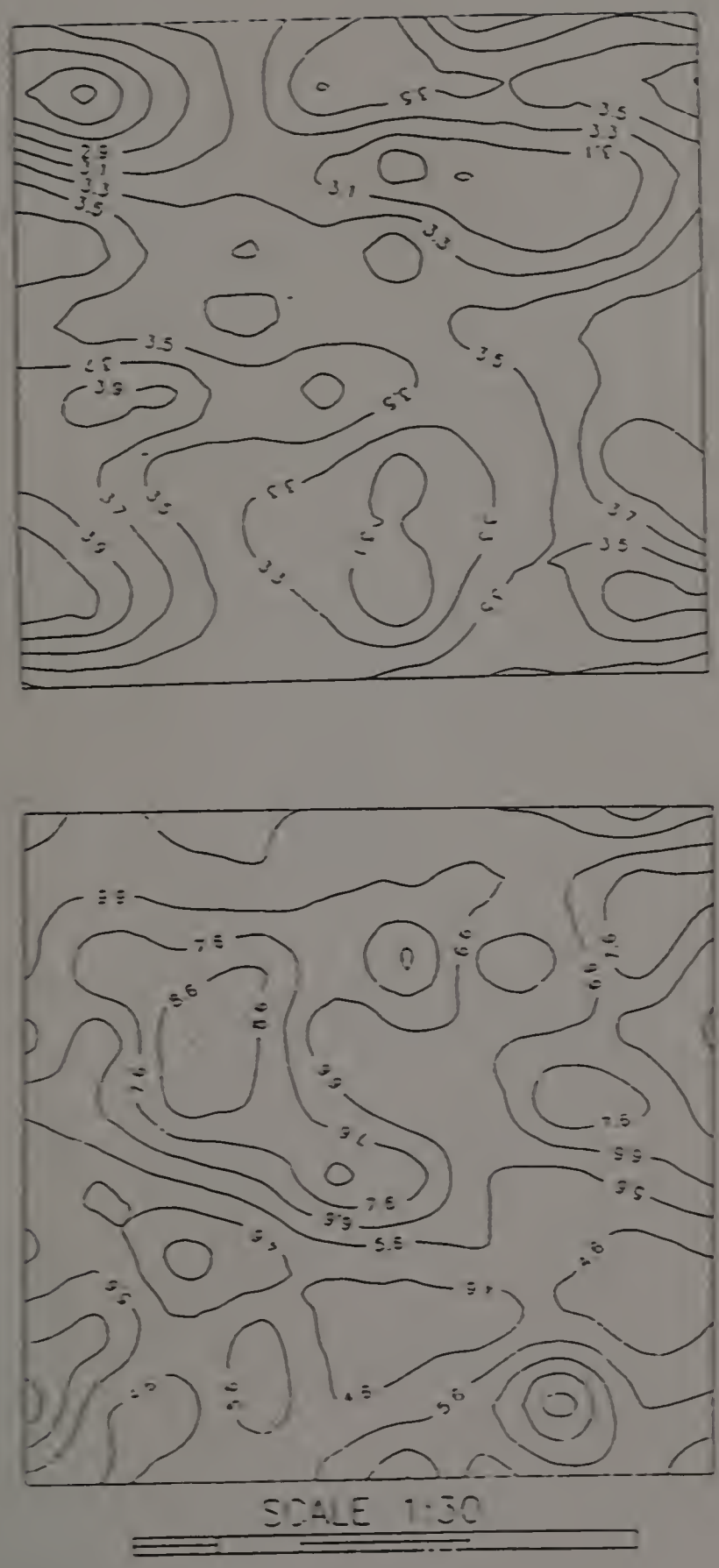

Fig. 4.13 Distribution of organic matter content (in percent) in an Agawam fine sandy loam mapping unit at two different locations.

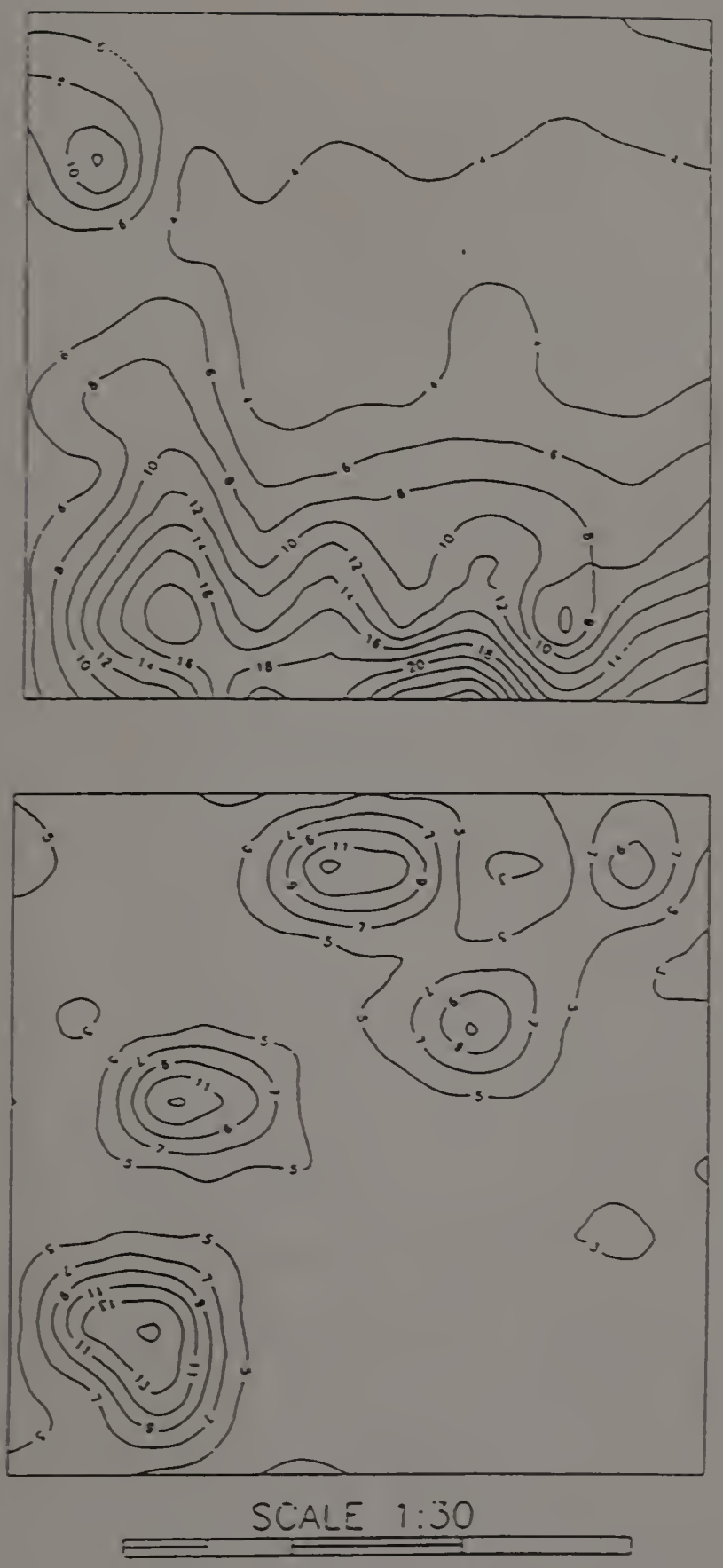

Fig. 4.14 Distribution of organic matter content (in percent) in a Limerick silt loam mapping unit at two different locations.

Table 4.1 Summary of analysis of variance for the organic matter content within different soil series.

Soil series	mean	SD	CV%	t ratio	DF
Hadley 1	4.54	1.09	23.94	1.64	92
Hadley 2	4.92	1.62	32.88		
Agawam 1	3.43	0.38	11.07	19.92**	111
Agawam 2	6.10	1.53	25.04		
Limerick 1	7.50	5.44	72.48	4.14**	151
Limerick 2	4.96	2.86	57.66		

*, ** significant at 0.05 and 0.01 levels respectively.

By selecting samples based on 30, 45, and 60 m sampling intervals from each studied grids, the same statistical analysis were employed (Table 4.2). Interestingly, by increasing the sampling interval, no significant differences were observed in the Hadley and Limerick soils with respect to organic matter variability. The low t-ratio in the Hadley mapping units compared to Agawam soils, may indicate the small degree of variability of organic matter content in those mapping units, which in turn implies that relatively small sampling sizes are sufficient to reasonably evaluate the variability in organic matter content in Hadley units.

The variability in organic matter content in various mapping units (Table 4.3) indicated that Hadley units in comparison to Agawam soil series, were not statistically different (F ratio < critical values). In contrast, there were significant differences between the Hadley versus Limerick, and Agawam versus Limerick mapping units (F ratio > critical values).

Variation of Organic Matter in Multi-Soil Series Transects

In mapping units comprised of more than one soil series, the delineations usually cannot be evaluated for variability in organic matter content in the same fashion as single series mapping units. To evaluate whether or not a higher degree of variability should be assumed, a 1200-m transect across a multi-soil series delineation including Hadley, Limerick, Hadley, and Agawam soils at 15 m sampling intervals, was analyzed for spatial dependency of the organic matter content (Fig. 4.15). The general pattern along the transect indicated less trend, and conversely, more autocorrelation. Geostatistics then were employed to determine the spatial dependency of soil organic matter content.

Experimental semivariograms were calculated (Robertson, 1987) for lag distances of 15 m by using the number of data pairs up to lag 600 m (Fig. 4.16). The semivariogram showed a damped periodicity, leveling in the range around 900 m. The semivariogram showed a high ratio of sill to nugget value (0.7 / 0.05) indicating appreciable autocorrelation

Table 4.2 T-ratios for comparison of variability of organic matter content within different soil series employing different sampling intervals.

Soil series	Interval sampling (m)	t ratio	DF
Hadley	30	0.425	30
	45	0.831	14
Agawam	30	9.850**	40
	45	6.225**	17
	60	6.563**	10
Limerick	30	2.474*	35
	45	1.834	18
	60	1.261	9

*, ** significant at 0.05 and 0.01 levels, respectively.

Table 4.3 F-values for cross comparison of variability of organic matter content in different soil series.

Soil series	F value[†]
Hadley vs. Agawam	0.008
Hadley vs. Limerick	16.137
Agawam vs. Limerick	22.264

[†] The obtained F ratios were considered significant if they were as large or larger than 11.08.

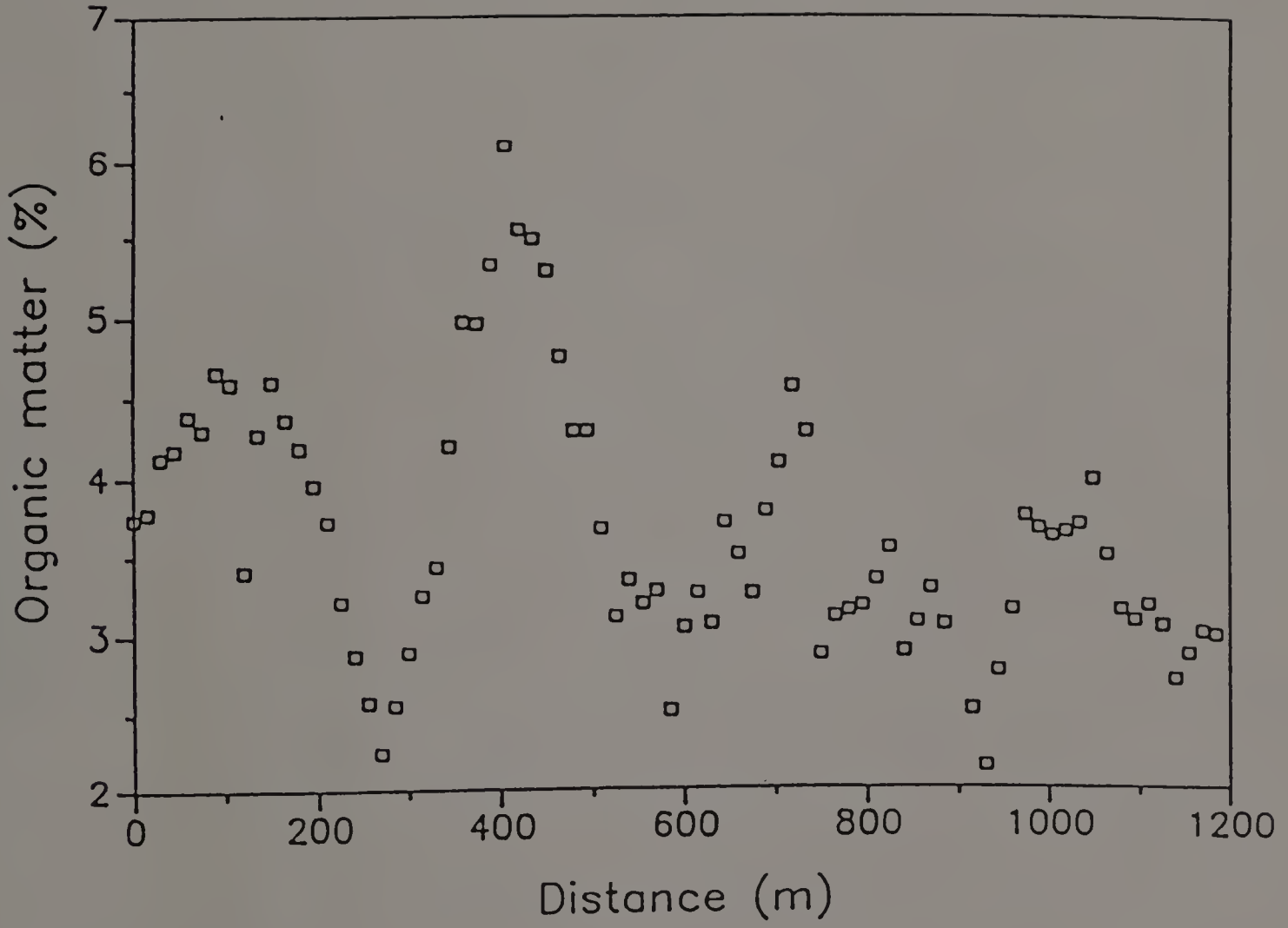

Fig. 4.15 Distribution of organic matter content along a multi-series transect including Hadley, Limerick, Hadley and Agawam soils. Sampling intervals were 15 m.

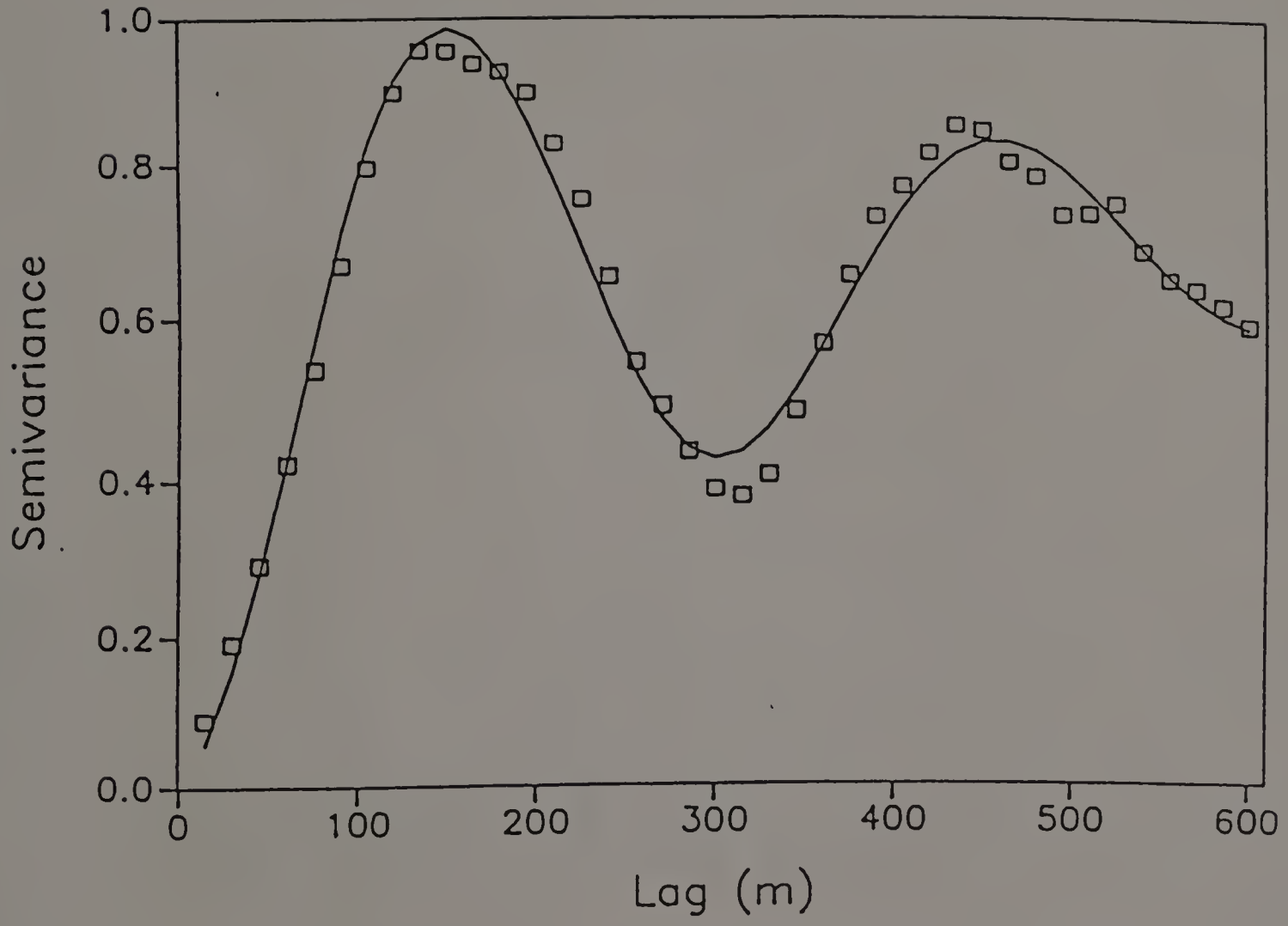

Fig. 4.16 Semivariogram of the soil organic matter content in the A-horizon along a multi-series transect including Hadley, Limerick, Hadley and Agawam soils, based on 15 m sampling intervals.

within transect. The semivariogram exhibited very little nugget effect. This small nugget effect indicates that the variation due to sampling error or the presence of the spatial structure within the entire distance is smaller than that of the sampling intervals.

The kriging procedure known as " jackknifing " was used to predict values for the organic matter content at sampled locations within the transect. Fitted plots of measured and predicted values showed a good correlation (Fig. 4.17). To verify the applicability of the kriging procedure, some measured values were deleted in developing the prediction model, where upon the missing values were predicted. Fig. 4.18 shows that predicted values are very close to the actual data with very small error bars.

Geostatistical methods were used to describe the structure of spatial dependency for organic matter content in two dimensions. For this purpose, a cultivated plot of land located in Hadley, Massachusetts was sampled in a grid pattern at 8 rows and 40 columns at 15 m sampling intervals. Sampling depth was 0 to 15 cm from the soil surface. The site included Hadley, Limerick, and Hadley soils along the row direction. Organic matter content was measured using the loss-on-ignition method (Davies, 1974). A three-dimensional plot of the measured values is shown in Fig. 4.19. The left and right sites in the grid represent the Hadley soils, and the middle part, with a high concentration of organic matter, is representative of the Limerick series.

One of the basic assumptions when applying kriging, is a normal distribution of the population. When the assumption of normality holds, kriging generally is a powerful prediction tool. The plot of obtained values of the percent of organic matter against the cumulative frequency of measured organic matter content revealed that actual data do not completely fit the normal distribution curve (Fig. 4.20). Logarithmic transformations of the percent organic matter, yielded a better normalized data set for use in subsequent statistical analysis (Fig. 4.21). Semivariograms based on the transformed organic matter values showed greater anisotropy (Fig. 4.22) in the X-direction than that of the Y-direction. To fit the

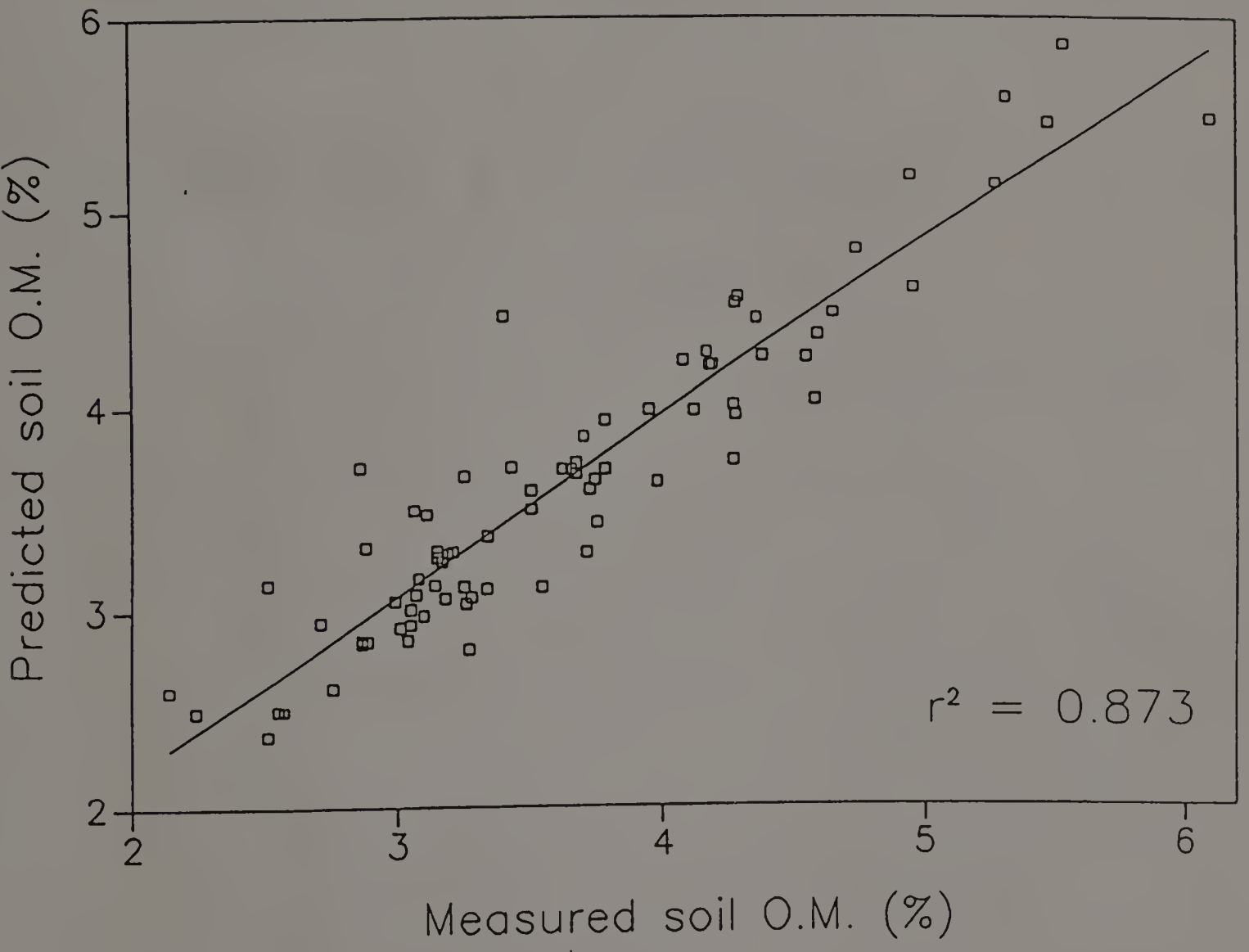

Fig. 4.17 Regression relationships between measured soil organic matter and predicted soil organic matter content using kriging within the multi-soil series transect, including Hadley, Limerick, Hadley and Agawam soils.

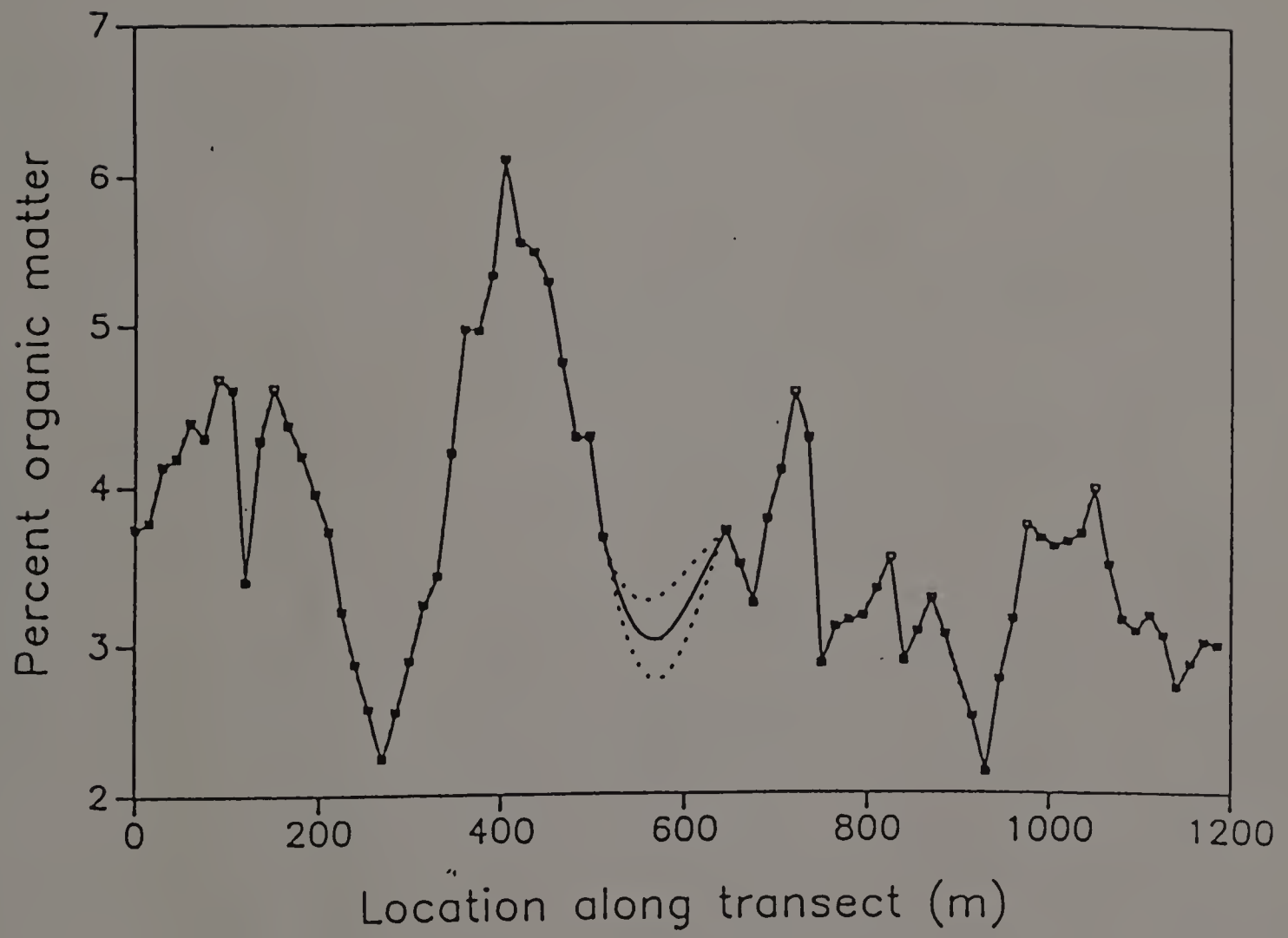

Fig. 4.18 Measured (squares) and predicted soil organic matter levels along a multi-series transect. The dashed lines show plus or minus two standard deviations of estimation.

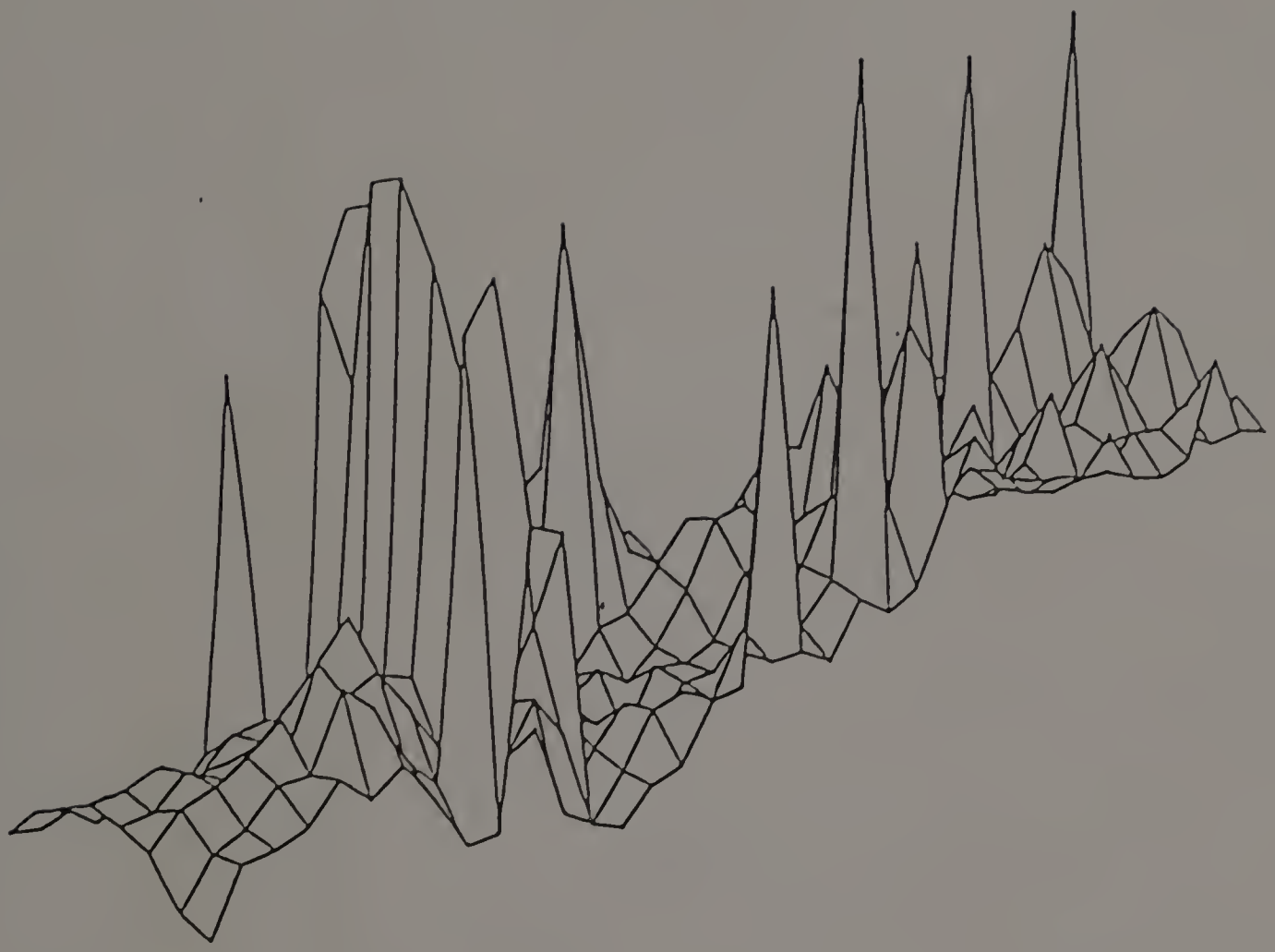

Fig. 4.19 Three-dimensional view of organic matter distribution within a grid including a Hadley-Limerick-Hadley sequence of soils.

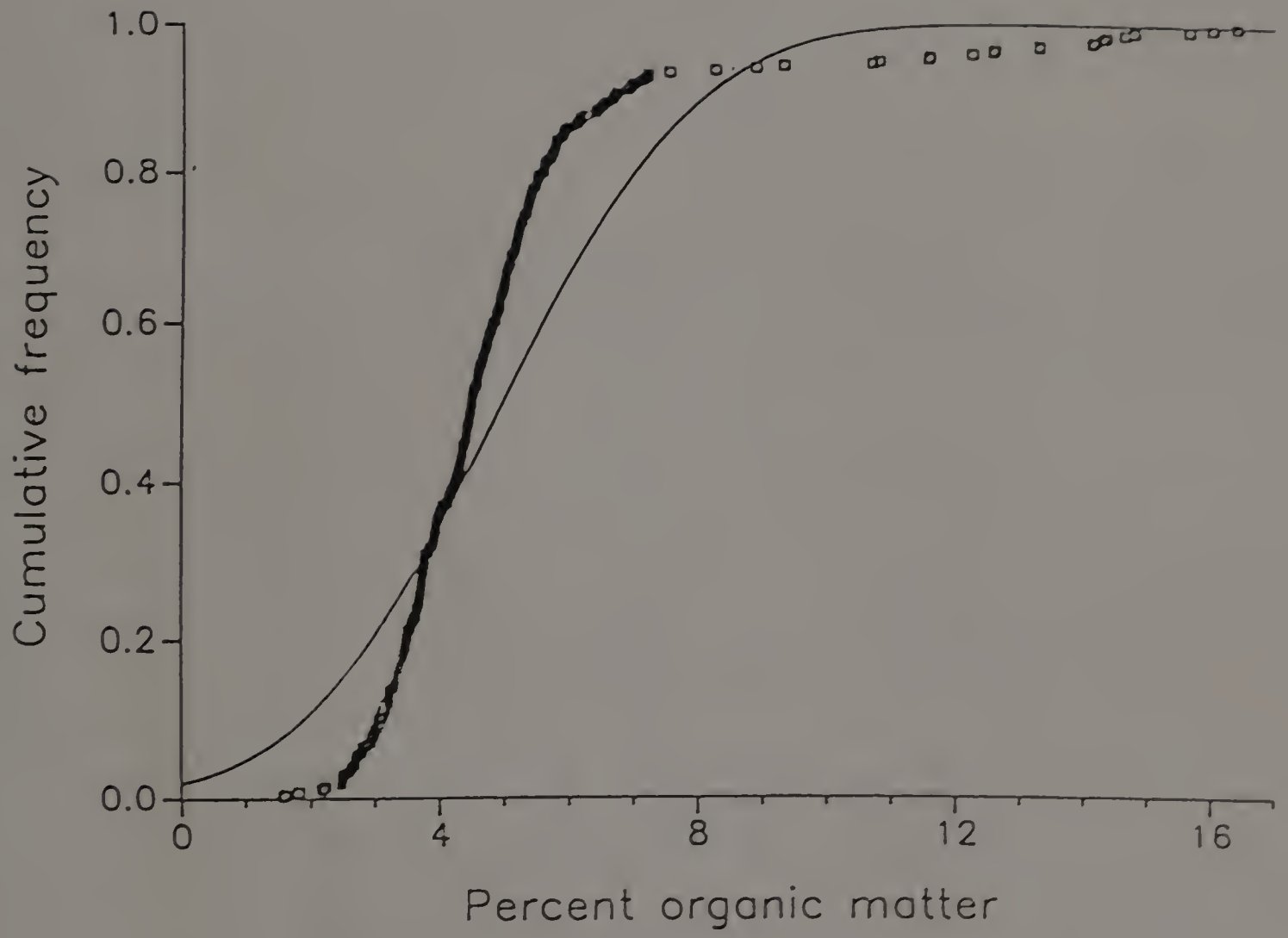

Fig. 4.20 Normal distribution of best fit to cumulative distribution of percent organic matter data from a grid including Hadley, Limerick, and Agawam soils.

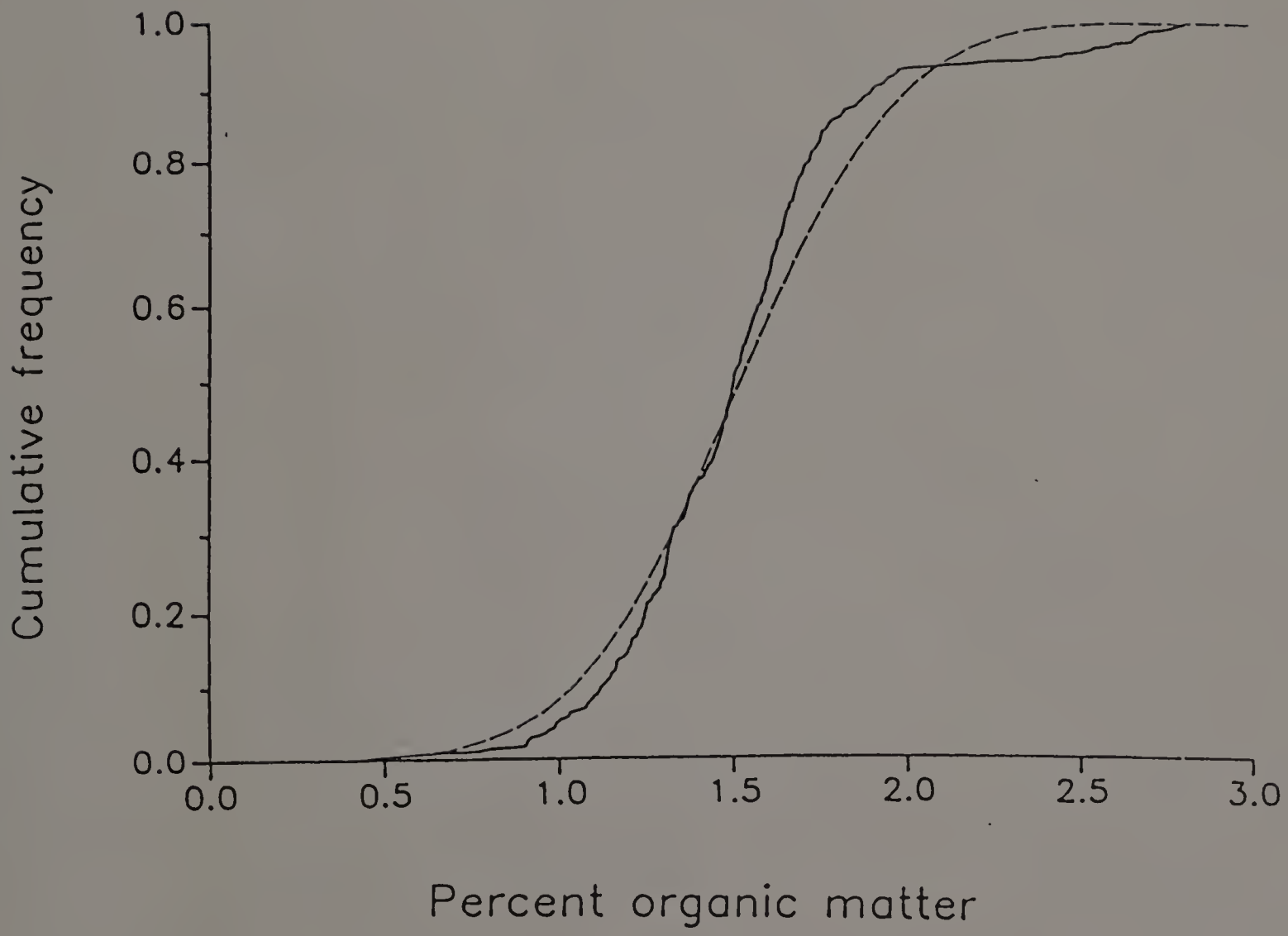

Fig. 4.21 Normal distribution of best fit to cumulative distribution of logarithmically transformed organic matter data from a grid including Hadley, Limerick, and Hadley soils.

semivariograms for kriging applications, the lag distance in the X-direction was expanded by the factor of 2.75 (Fig. 4.23).

Fig. 4.24 shows the exponential model (Webster, 1985) fitted to the pooled semivariogram. Modeling for anisotropic semivariograms permitted identification of the changes in spatial variability with respect to the direction in the study site, which in turn, is a reflection of the nature of processes taking place in the soil.

Jackknifing is a procedure in kriging in which values at a measured site are estimated using values from the surrounding known sites, and compares the estimated values to the measured data. A positive, although not very strong correlation (r^2 = 0.438) between jack-knifed and measured values for organic matter (Fig. 4.25) was found in the Hadley grid.

Transformed values of organic matter content were block kriged in 5.45 × 15 m^2 cells over the studied grid (Fig. 4.26). The range of kriged values is shown as a spectrum of shaded colors. Dark shaded regions across the grid stand for high concentrations of organic matter, and lighter colors indicate sites of lower concentration in organic matter. The pattern of kriged values in the Hadley grid demonstrates the heterogeneous distribution of organic matter in the landscape. The highest values mostly coincide with the Limerick soils, whereas the other regions are representative of Hadley soils.

The general spatial variability pattern of soil organic matter content and its heterogeneity was explained mostly by differences between different soil series. In general, in the sites within single mapping units, a trend was evident, precluding autocorrelation in single mapping units.

The of variance in organic matter content in Hadley and Agawam soils was small. In contrast, it was quite large in the Limerick soil series. Analysis of the spatial dependence of organic matter in short and long transects including single series mapping units using semivariograms, indicated that variation of the soil organic matter content was generally so autocorrelated as to exhibit trend. Sampling intervals at 0.5, 1, and 15 m in single

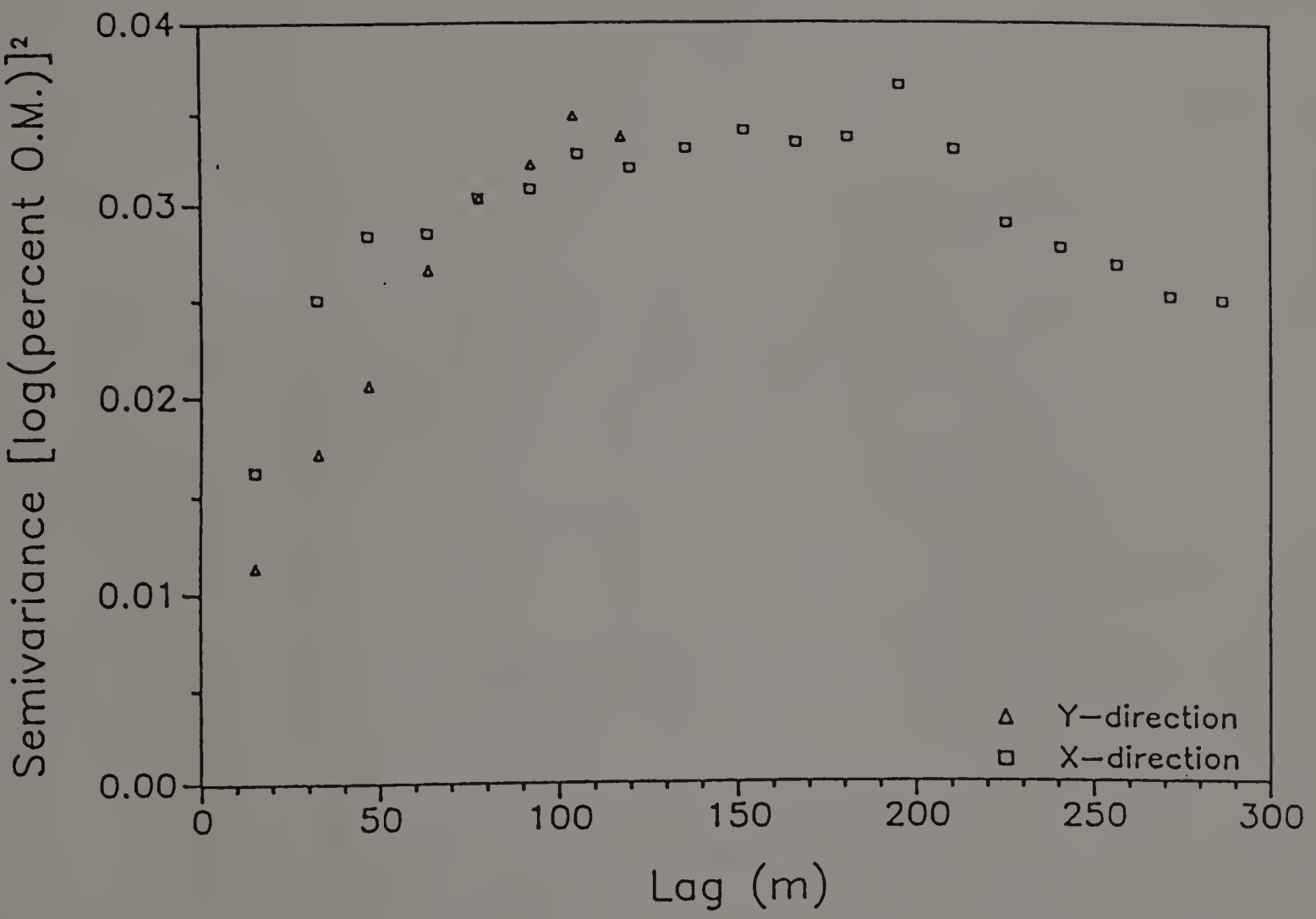

Fig. 4.22 Evidence of anisotropy of logarithmically transformed organic matter values in the Hadley-Limerick-Hadley grid.

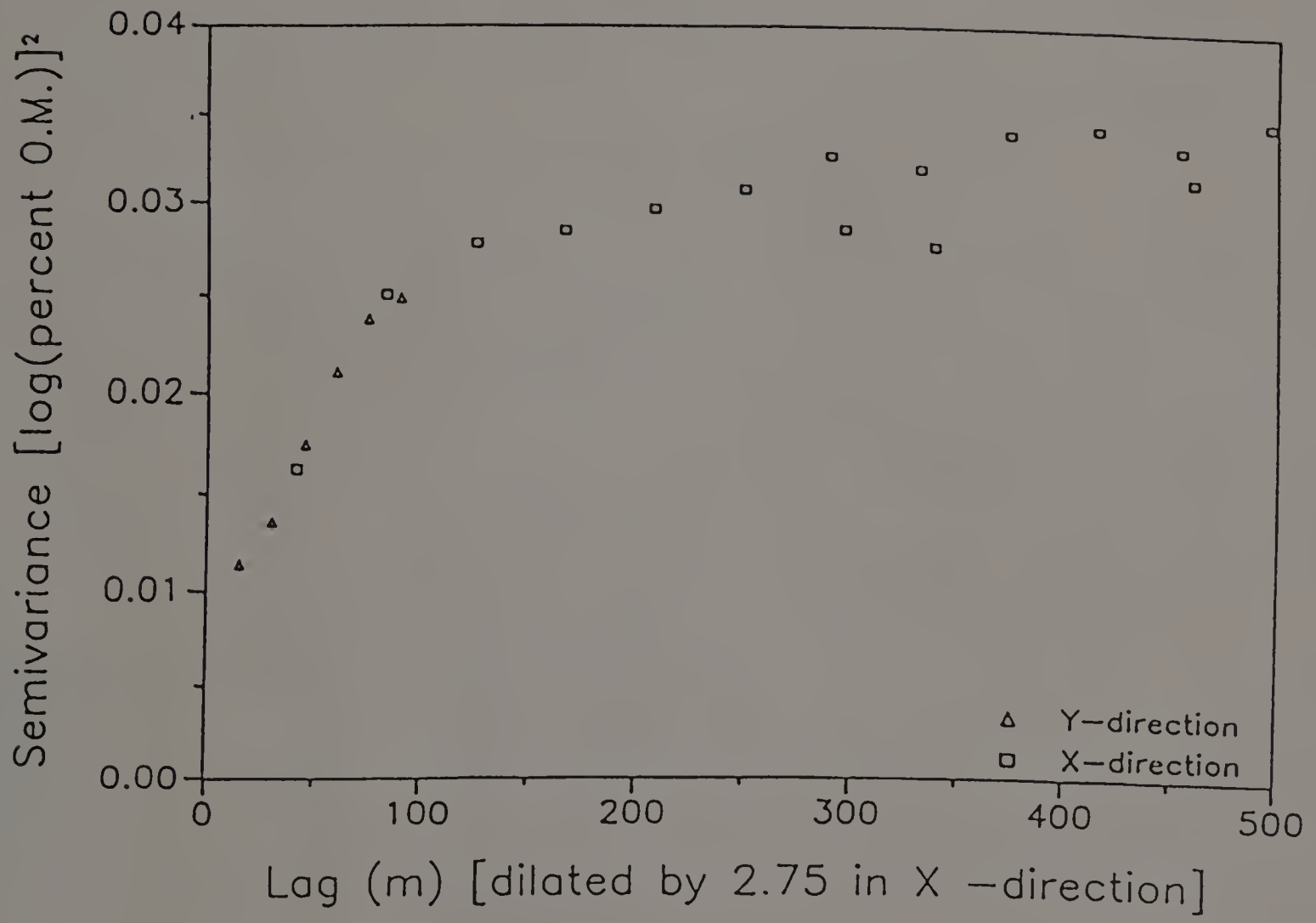

Fig. 4.23 Evidence of isotropy of logarithmically transformed organic matter values in the Hadley-Limerick-Hadley grid. The lag distance in the X-direction has been expanded by a factor to obtain an improved fit.

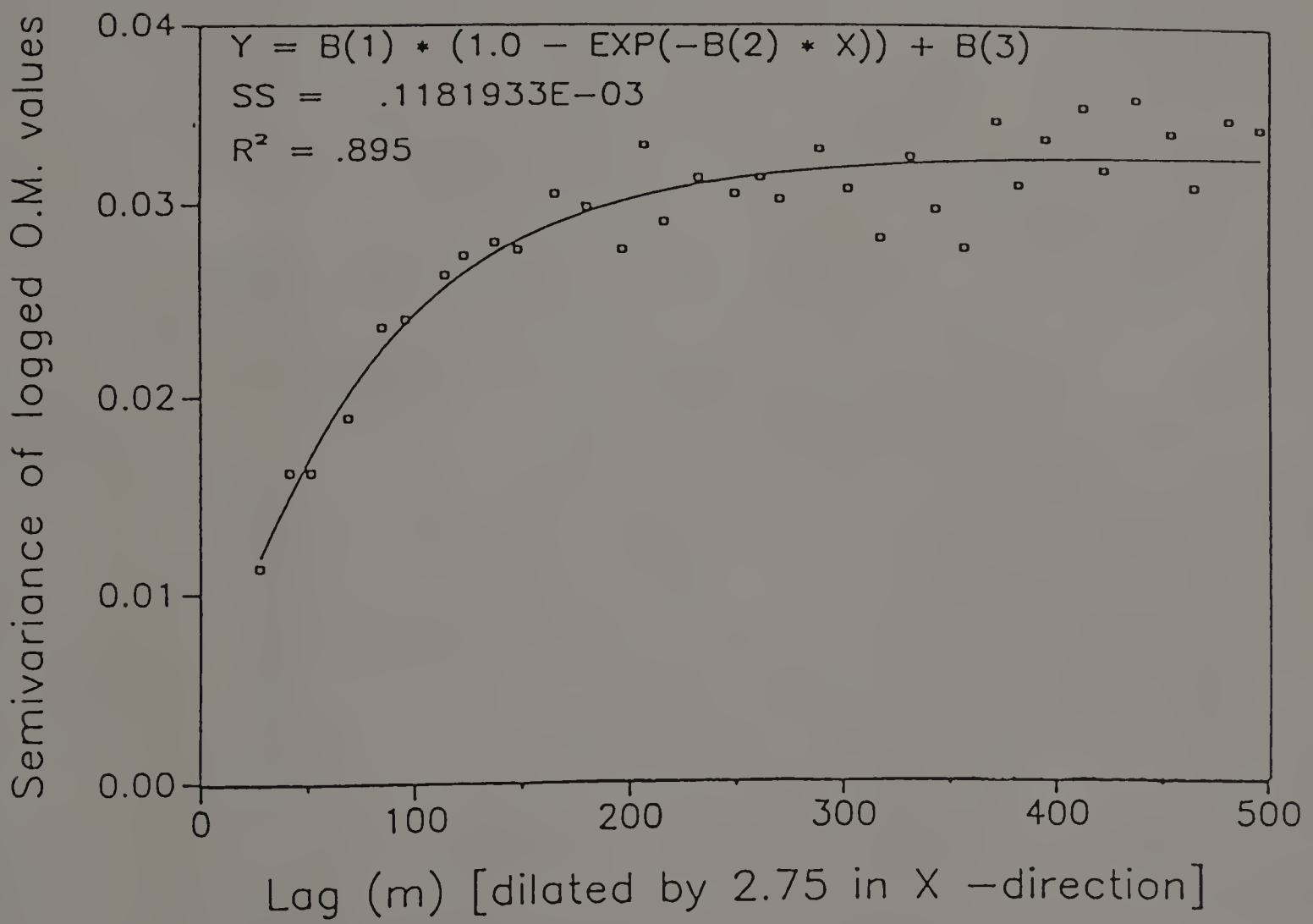

Fig. 4.24 Overall semivariogram and fitted equation for logarithmically transformed organic matter values within the Hadley-Limerick-Hadley grid.

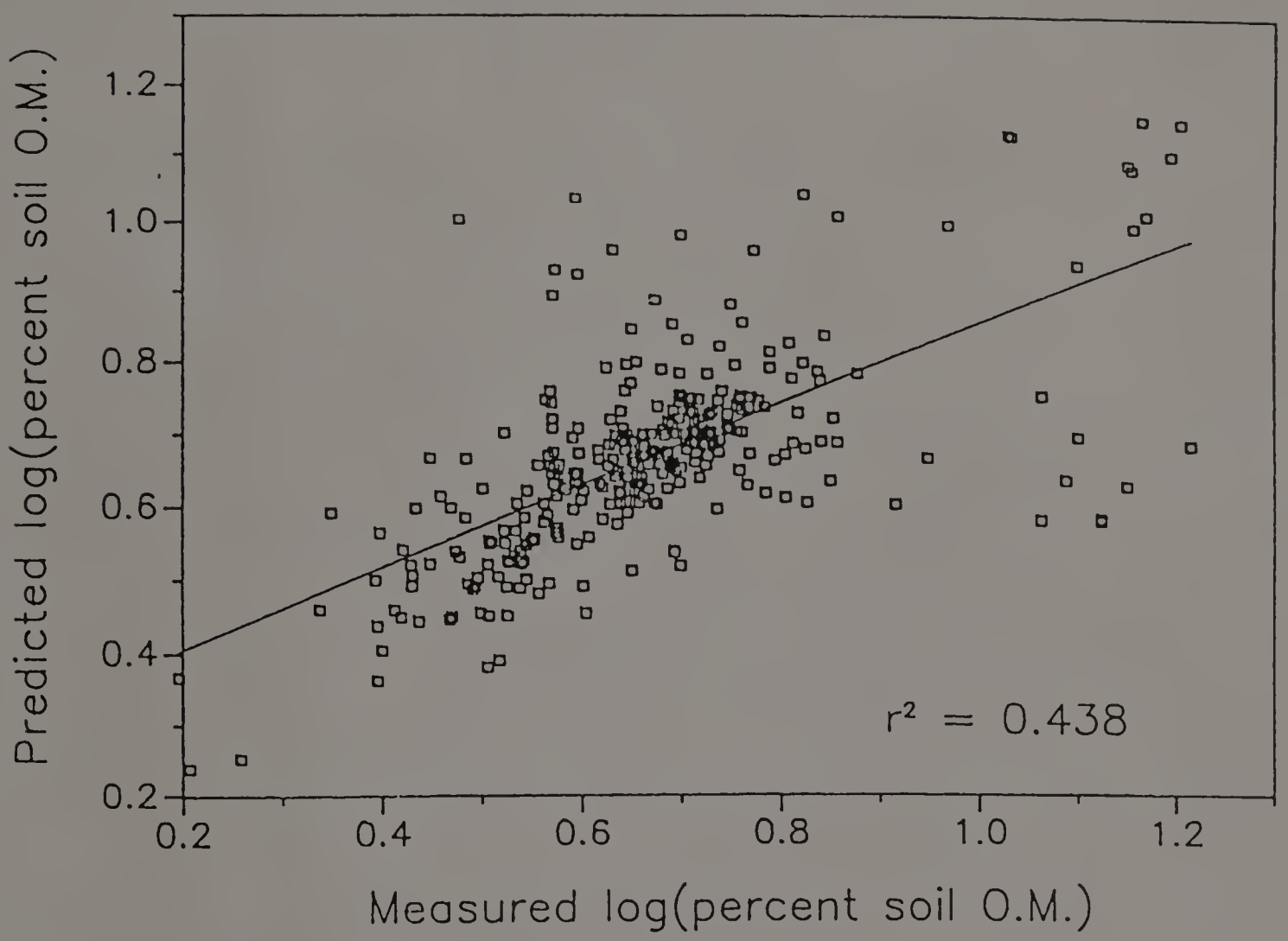

Fig. 4.25 Agreement between jackknifed and measured organic matter values for Hadley-Limerick-Hadley grid.

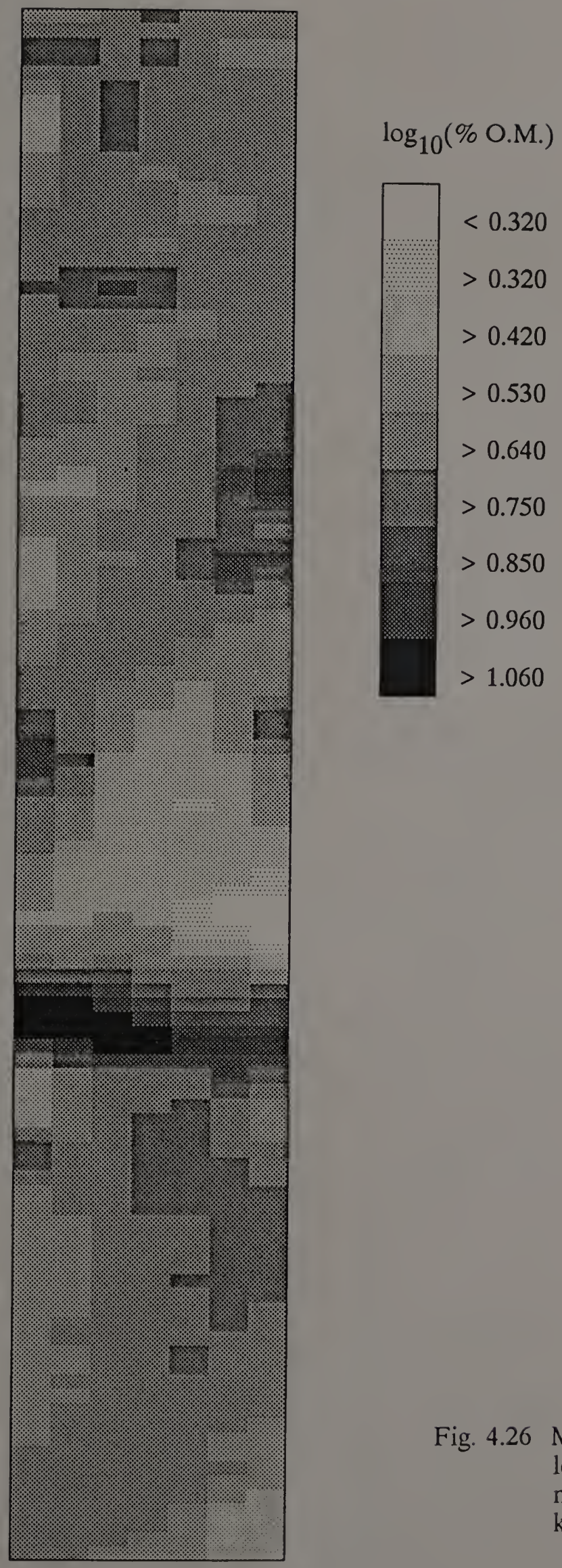

Fig. 4.26 Map of Hadley grid showing average logarithmically transformed organic matter levels calculated by block kriging.

mapping units along both short (50 and 80 m) and long (1200 m) transects, indicated that geostatistics could not be applied.

Both the transect and grid containing multiple soil series, indicated a better spatial dependency for organic matter content. It was also apparent that organic matter does not accumulate to the same degree in all soils studied, which may be caused by differences in drainage class. Hadley and Agawam soils are deep and well- drained. The texture of the surface horizon in these soils is silt loam (Hadley) and fine sandy loam (Agawam). The lack of strong mottling features in the subsoil indicates good aeration, hence, acceleration in the rate of organic matter decomposition. On the other hand, Limerick soils consist of deep, poorly or somewhat poorly drained soils on floodplains. They typically have silt loam textures. The presence of mottles in the subsoil shows the presence of a seasonal high water table which may decrease the rate of microbial breakdown of organic compounds.

Conclusions

The distribution of organic matter along short and long transects, and also within and between soil series including single mapping units, was found to exhibit strong trend, regardless whether 0.5, 1, or 15 m sampling intervals were used. Such a condition may be statistically analyzed by taking random or grid samples and applying classical statistics to provide mean, standard deviation, variance, standard error, regression and coefficient of variation as estimators in the variability of organic matter content. On the other hand, at locations where multiple soil series are considered, it is likely to have significant autocorrelation in the organic matter distribution. In this case, geostatistical analysis using 15 m sampling intervals and kriging to predict values for unsampled locations, is recommended in the evaluation of spatial dependency of organic matter content.

CHAPTER V

CONCLUSIONS

Determination of the spatial variability of organic matter in selected Massachusetts soils was the purpose of this study. Prior to initiation of the variability study, data from the rapid loss-on-ignition method was compared to that of wet oxidation and dry combustion methods. The results showed a significant correlation between the loss-on-ignition and the other methods ($0.53 \leq r \leq 0.99$). This was true in the A, B, and C horizons in the soil series studied.

The results indicated that the loss-on-ignition method, particular in A and B horizons, was representative of wet oxidation and dry combustion procedures ($0.90 \leq r \leq 0.98$). Regression with standard soil characterization data showed that organic matter content values can be accurately predicted based on extractable Al, CEC, and clay content values.

Spatial variability of organic matter content was studied through application of geostatistical methods. The organic matter distribution in the topsoil in short (50 and 80 m) and long (1200-m) transects, indicated the presence of strong trend at sampling distances of 0.5, 1, and 15 m.

Studies in single and multi-mapping units revealed that 15 m sampling intervals provided an appropriate distance for organic matter content evaluation. Geostatistical analysis of data obtained from short and long transects within single mapping units, indicated that the semivariograms did not indicate spatial dependency of organic matter content after strong trends were removed by regression. Classical statistical analysis revealed that there was no significant difference (t ratios < critical values) in organic matter content variability within two Hadley soil mapping units. In contrast, the organic matter

content within the Agawam and Limerick soil series (t ratios > critical values) was significantly variable.

Study of the organic matter variability between different soil series indicated no significant differences between the Hadley and Agawam soils (F ratios < critical values), but, there were a significant differences between the Hadley verses Limerick, and Agawam verses Limerick (F ratios > critical values) soil series.

Analysis of multi-series mapping units, both with transect and grid, revealed evidence of spatial dependency for organic matter distribution. Kriging was used to predict organic matter content at unsampled locations. There was significant correlation (r^2 = 0.873 for transect) and (r^2 = 0.438 for grid) between measured and predicted values in studied sites. The results also indicated the presence of anisotropy in the grid studied. This showed that the number of samples should be increased by the factor of 2.75 in the X-direction. A map of the organic matter levels in the Hadley grid indicated that these levels could be calculated using block kriging procedures.

APPENDIX A

Soil Profile Description

Hadley Series

Location: Hadley, Hampshire County, Massachusetts.

Classification: Typic Udifluvent (coarse-silty, mixed, nonacid, mesic)

Sampling date: 8/18/1989

Drainage class: Well-drained

Slope: 1%

Parent material: Alluvium

Land use: Cornfield

Horizons	Description
Ap	0-32 cm; dark brown (10YR 4/3); fine sandy loam; weak medium granular structure; friable; many fine roots; abrupt smooth wavy boundary.
Bw1	32-59; light brown (5Y 4/4) silt loam; massive; friable; common yellowish brown (10YR 4/4) mottles; smooth boundary.
BC	59-76 cm; light brown (5YR 4/4) fine sandy loam; massive; very friable; smooth boundary.
C	76-130^{+} cm; light olive brown (2.5YR 5/4) sandy loam; very friable.

Limerick Series

Location: Hadley, Hampshire County, Massachusetts.

Classification: Aeric Fluvaquent, (coarse-silty, mixed, nonacid, mesic)

Sampling date: 8/18/1989

Drainage class: Poorly drained

slope: 4%

Parent material: Alluvium

Land use: Cornfield

Horizon	Description
Ap	0-13 cm; dark grayish brown (10YR 4/2) silt loam; moderate granular structure; friable; few fine roots; abrupt smooth boundary.
C1	13-36 cm; slightly dark brown (5YR 4/3) silt loam; massive; friable; some fine roots; a few yellowish (10YR 6/8) mottles; friable; wavy boundary.
C2	36-110 cm; grayish brown (5YR 4/3) silt loam; massive; friable; some yellowish (10YR 6/8) mottles; regular boundary.

Agawam Series

Location: Hadley, Hampshire County, Massachusetts.

Classification: Typic Dystrochrept (coarse-loamy over sandy-skeletal, mixed mesic)

Sampling date: 8/18/1989

Drainage class: Well-drained

slope: 2%

Parent material: Glacial outwash

Land use: Cornfield

Horizons	Description
Ap1	0-18 cm; yellowish brown (10YR 3/3) fine sandy loam; weak granular structure; friable; many fine roots; wavy boundary.
Ap2	18-34 cm; dark yellowish brown (10YR 3/2); fine sandy loam; medium granular structure; friable; a few fine roots; uncontinuous; wavy boundary.
Bw	34-58 cm; yellowish brown (10YR 5/6) fine sandy loam; weak granular structure; friable; clear smooth boundary.
2C1	58-80 cm; light olive (2.5Y 5/2) medium sand; loose; smooth boundary.
2C2	80-120 cm; light olive (2.5Y 5/2) coarse sand; very loose; smooth boundary.

APPENDIX B

A Brief Review of Geostatistics

GEOSTATISTICAL CONCEPTS

In agricultural sciences, the assumption of independent observations is not always met (Sabbe and Marx, 1987). In most cases, the variables are spatially dependent. In this circumstance, the classical statistical methods of data analysis, which assume that the observations are randomly distributed and spatially independent regardless of their location in the field are no longer valid techniques. In classical statistical methods, mean, variance, standard deviation and coefficient of variation can be estimated for various soil properties. This method does not provide a clear picture of the true distribution of the soil properties, because the calculated variance does not account for the distance between observations (Saddig et al., 1985).

A new approach to spatial statistical analysis, known as geostatistical methodology or regionalized variable theory, considers differences between pairs of values of a particular soil property at different locations, expressed as a function of the distance between the sampling locations (Webster, 1985). Studies show that there is often some degree of dependency between sample values as a function of the distance between samples (Warrick and Nielsen, 1980; Hajrasuliha et al., 1980 ; Vieira et al., 1981). These relationships can be expressed in semivariograms and autocorrelograms to indicate the nature of changes for any given soil property in the field in relation to distance and degree of dependency among neighboring observations. These functions also indicate the maximum sampling distance for which the observations remain correlated, i.e. where the autocorrelograms level off after a steady decay (Webster, 1973). Depending on the soil properties under consideration, the maximum sampling distance may vary from a few centimeters to several dekameters (Gajem et al., 1981). For example, Saddig et al. (1985) concluded that the number of measurements of the infiltration rate could be decreased from 1280 samples to 128 samples, without any significant loss in accuracy. Riha et al. (1986) reported that the spatial variability of pH and organic matter in forested plantations could be adequately assessed by selecting five meter

sampling intervals along east-west and north-south transects. Fundamental concepts in the geostatistical method are:

i. Development of an autocorrelation function.

ii. Development of a semivariogram function.

iii. Application of models for interpreting semivariograms and autocorrelograms.

iv. Kriging.

Autocorrelation Function

Autocorrelation functions are an expression of changes in field-measured soil properties over distance and the degree of dependency among neighboring observations. This function (Fig. B.1), is estimated from equation 1 (Warrick and Nielsen, 1980):

$$r_k = c_k / s^2 \qquad \text{(eq.1)}$$

with

$$c_k = [1/(n-k-1)] \sum_{i=1}^{n-k} [z_{(i)} - s][z_{(i+k)} - s] \qquad \text{(eq.2)}$$

where:

r_k = autocorrelation at lag k,

n = number of observations,

k = relative distance between the observation being compared, $k = h/\Delta x$, where Δx is the distance between adjacent observations,

$z_{(i)}$ = value of the observation at the i-th position,

$z_{(i+k)}$ = observation at the (i+k)-th position,

c_k = autocovariance,

s = standard deviation of the series.

High values of r_k represent a strong relationship between the observations separated by a distance equal to h, ($h = k \cdot \Delta x$). Low values suggest a highly variable distribution.

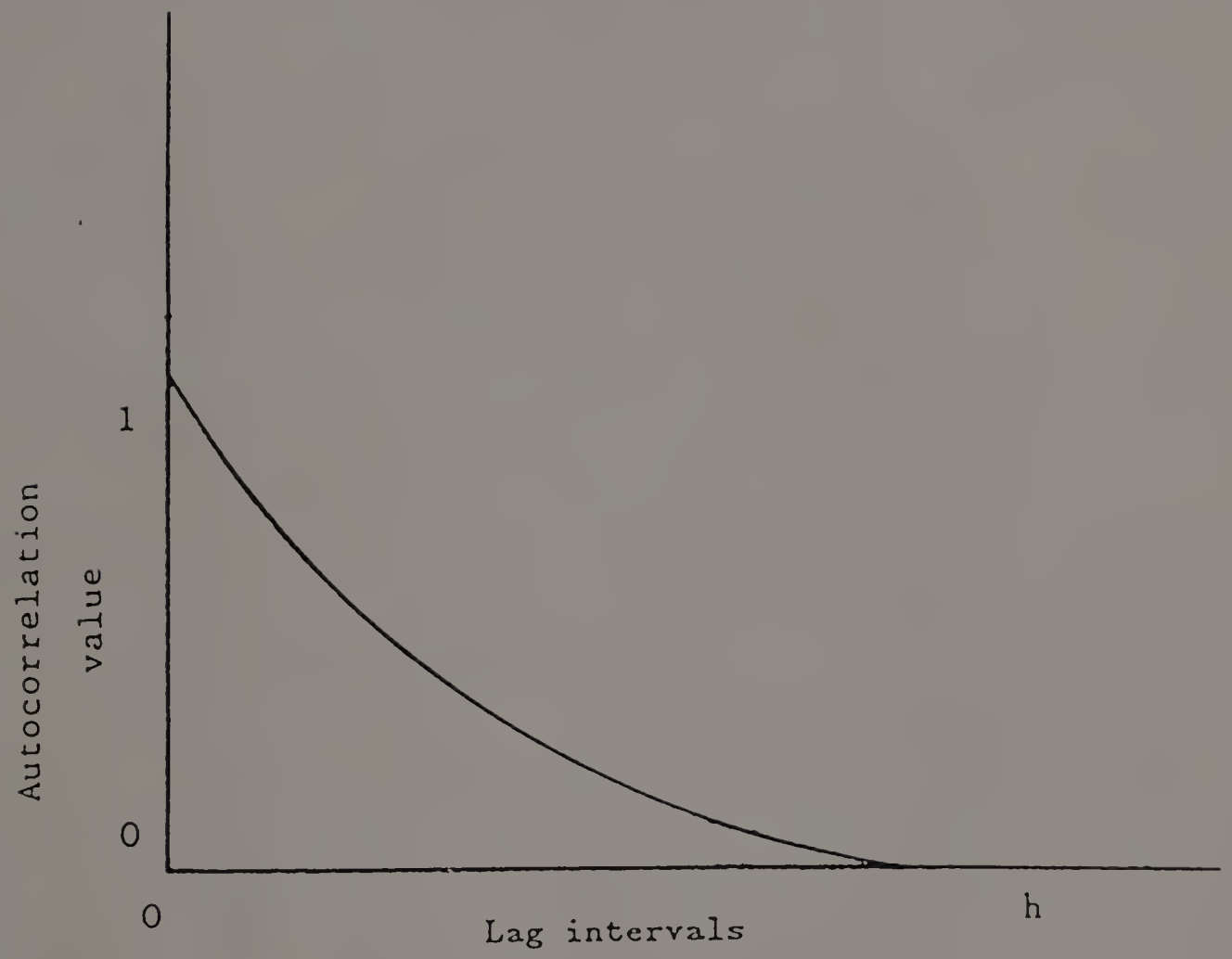

Fig. B.1 Example of an autocorrelogram.

Values of r_k at or near zero, indicate no relationship between values separated by the distance indicated by k (Dahiya et al., 1984). The graphical representation of the values of r_k versus lag k, is known as an autocorrelogram.

Semivariogram Function

The semivariogram is a tool to estimate the average rate of the regionalized variable over any distance. The semivariogram function is estimated from equation 3 (Rendu, 1978),

$$\gamma[h] = 1/2\ E\{[z_{(x)} - z_{(x+h)}]^2\} \qquad \text{(eq. 3)}$$

where:

$\gamma[h]$ is a measure of the estimated variance,

$z_{(x)}, z_{(x+h)}$ are the sample values of z at locations (x) and (x+h), respectively, and

$E\{[z_{(x)} - z_{(x+h)}]^2\}$ is the expected squared difference between values of samples separated by lag distance h.

h is the lag distance, and

n is the number of observations.

The plot of $\gamma[h]$ versus h is called a semivariogram (Fig. B.2).

The important characteristics of a semivariogram are:

Sill, Which indicates the maximum level of the semivariogram minus the nugget vaiance.

Range, which reveals the lag at which the semivariance reaches the maximum sill value.

Nugget Variance, which shows the intercept of the semivariance at zero lag spacing.

The range value expresses the distance beyond which the values of the samples are no longer correlated, and it indicates the limit of spatial dependency. In other words, the points within the range are spatially dependent, while, those further apart, have no relation to one another. When the semivariogram becomes parallel to the x axis (h), it indicates that the values of $\gamma(h)$ are the same for each possible sampling interval, h (Dahiya et al., 1984).

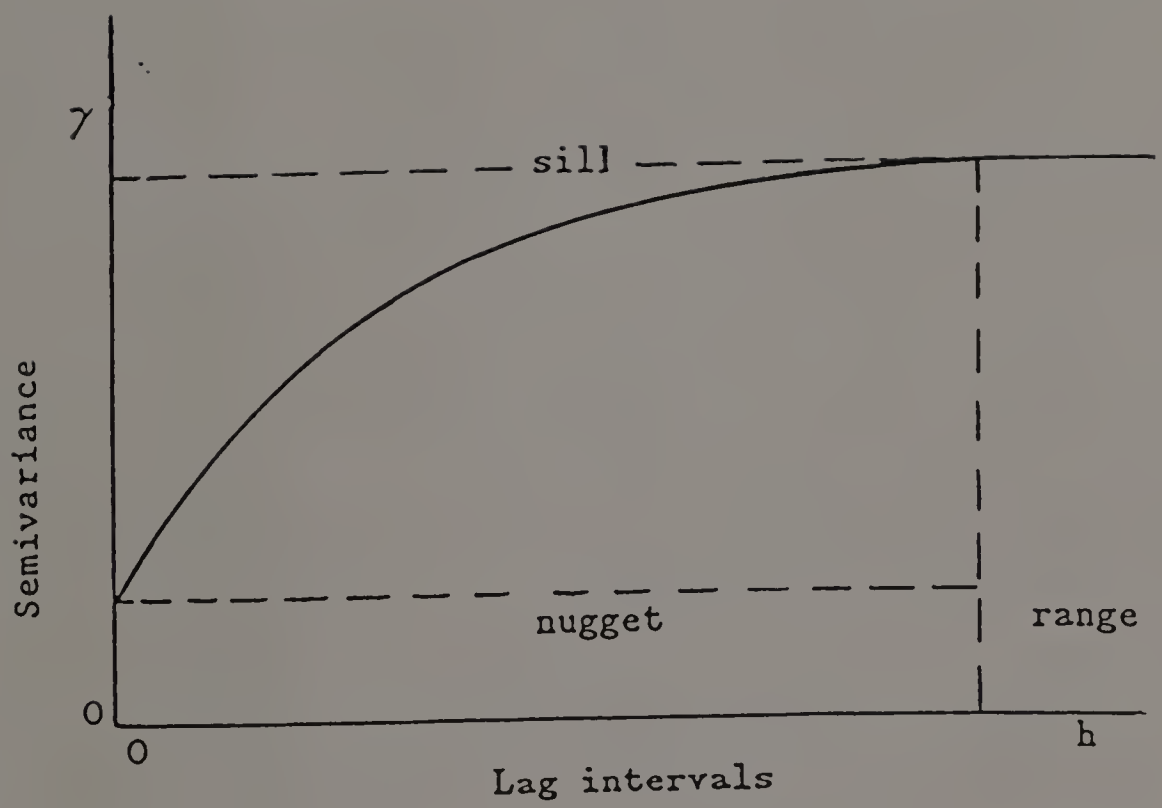

Fig. B.2 Example of a semivariogram.

With the following formula (Yost et al., 1982) it is possible to estimate the spatial variability of any component in two dimensions:

$$\gamma(\alpha, h) = \Sigma\{[z_{(x)} - z_{(x+h)}]^2\} / 2n \qquad \text{(eq. 4)}$$

in which the term of (α) indicates the angle or direction modulated by (h) or interval distance between the any two points.

The semivariogram is related to the autocorrelogram (Burgess and Webster, 1980; Gajam et al., 1981; Bresler et al., 1982) by following equations:

$$\gamma(h) = s^2 (1-r_k) \qquad \text{(eq. 5)}$$

or

$$r_k = 1-[\gamma(h) / s^2] \qquad \text{(eq. 6)}$$

Models for Interpreting Semivariograms and Autocorrelograms

Mathematical expressions can be developed for the semivariogram and autocorrelogram. These models (Fig. B.3), include the following:

-Linear model $\quad \gamma(h) = \alpha h \quad$ for $h < a$

$\gamma(h) = \sigma_0^2 \quad$ for $h \geq a$

-Spherical model $\quad \gamma(h) = \sigma_0^2 (3h/2a - h^3 /(2a^3))$

-Exponential model $\quad \gamma(h) = \sigma_0^2 (1-e^{-h/a})$

The applicability of a particular model will obviously be governed by the general graphic appearance of semivariogram (Webster, 1985).

Kriging

Kriging is a procedure to estimate the value of a particular property at any unsampled location. It is essentially a means of weighted local averages, in which the weights are chosen so as to give an unbiased estimate, while at the same time minimizing the error

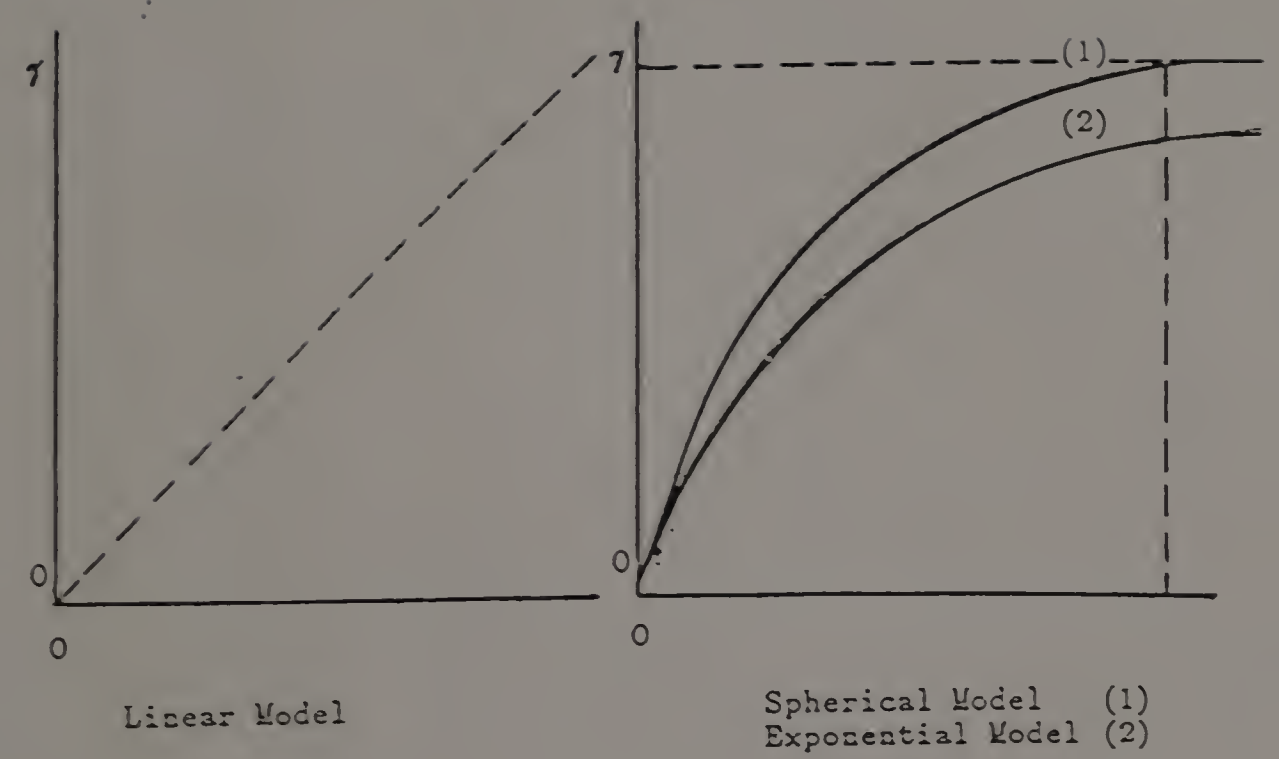

Fig. B.3 Example of a basic mathematical expression of semivariograms.

of estimation. Kriging uses information from a semivariogram to find an optimal set of weights that are used in the estimation of a soil variable at unsampled locations. Through this procedure, the value for any unsampled location (P), is estimated as a weighted average of the known observations. For example, a kriged estimate of the value Y at a point p (Y_p), from three known observations Y_1, Y_2, and Y_3, may be calculated as:

$$Y_p = W_1 Y_1 + W_2 Y_2 + W_3 Y_3$$

once the unknown weights, w_i, have been determined (Davis, 1986).

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